Acta Geologica Polonica, Vol. 54 (2004), No. 3, pp. 413-432

Influence of soil-water conditions on the migration of pollutants in the vicinity of municipal landfill sites

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ABSTRACT:

ZŁOTOSZEWSKA-NIEDZIAŁEK, H. 2004. Influence of soil-water conditions on the migration of pollutants in the vicinity of municipal landfill sites. *Acta Geologica Polonica*, **54** (3), 413-432. Warszawa.

The time taken for a pollutant to migrate from the potential source to the groundwater reservoir is one of the main criteria in evaluating groundwater hazards. This process depends on the lithology and thickness of the deposits forming the basement of the landfill site as well as on the depth to the groundwater table, infiltration and the concentration of effluents. This paper focuses on the analysis of the influence of particular factors on the transport of pollution, based on field analyses and numeric modelling. The Femwater program was applied in numeric calculations. This program solves a 3-D modified RICHARDS equation for groundwater flow by the finite elements method (FEM), and the mass transport equation using the hybrid LAGRANGE – EULER finite elements method. The results obtained allow evaluation of the influence of the soil-water environment factors that determine the rate of pollution distribution and are the basis for forecasting the processes concerned in the migration of pollutants. The problem was solved in two examples of municipal waste landfill sites characterised by a different geological setting, one located on the supra-flood terrace in the River Vistula valley and the other on the Wołomin Plateau.

Key words: Geological conditions, Landfill sites, Water analysis, Migration of pollutants, Numeric calculations.

INTRODUCTION

Municipal wastes in Poland are usually stored in randomly selected post-exploitation pits or on wastelands. These objects are the source of possible hazard to the soil-water environment, and the typical lack of controlling and measuring systems does not allow evaluation of their influence on the surroundings.

At present, the legislation relating to protection of the natural environment is increasingly tighter. The strategy of groundwater protection is realized already at the level of town and country planning, to locate the potentially hazardous objects in such geological conditions, which would optimally protect the soil-water environment from the migration of effluents. Therefore the analysis of the influence of existing landfill sites (exploited and abandoned) on the quality of groundwater in different geological conditions is of crucial value in evaluating the methodology of forecasting the migration of pollutants

The efficiency of groundwater protection is based mainly on the accuracy of forecasts describing the migration of pollutants. Processes of mass transport in groundwater are very complex due to the great variability of properties of the polluting agents and the phenomena that accompany migration.

Modelling the groundwater circulation scheme and the transport of pollutants linked with it is possible by means of the application of computer simulation programs. The obtained results allow for the conclusions evaluating the influence of environmental factors controlling the rate of pollutants distribution. They are the basis for forecasting the processes of their migration.

OBJECTIVES OF ANALYSES

The aim of the analyses was the identification, on the basis of selected municipal landfill sites, of the factors controlling the distribution of pollutants and the evaluation of their influence on the flow rate in typical soil-water conditions in the Mazovian Lowlands.
The analyses includes:

- selecting the investigation polygons;
- selecting the model of groundwater circulation in particular types of hydrogeological conditions;
- numeric calculations of flow and transport of pollutants in different hydrogeological conditions occurring within the experimental polygons (Boża Wola and Lipiny Stare);
- evaluating the influence of soil-water conditions on the rate of distribution of pollutants.

CONTROLLING THE MIGRATION OF POLLUTANTS

The criteria for the selection of areas for a landfill site were widely discussed (Błaszyk & Górski 1996, Drągowski 1989, 1997 b, Kempa1993, Kolago 1974, 1986, Piotrowska 1993, Rosik-Dulewska1999 and Wysokiński1997). Various conditions linked with selecting the proper location and factors influencing the distribution of pollutants in the soil-water environment were presented. The spatial range of possible hazard caused by the landfill site on the groundwater quality is connected with the conditions affecting the migration of pollutants and the type and quantity of effluents. Each polluting agent may migrate in a variable way, dependent on the conditions in question, and consequently proper evaluation of its migration requires site-specific analysis. Therefore, in practice, forecasting the degree of groundwater hazard caused by a surface source is based on evaluation of the protective abilities of the overlying deposits in relation to their thickness and lithology.

It has been assumed that lithological complexes with variable thicknesses and permeability may play the role of a geological barrier (Kleczkowski & *al.* 1984; Kolago 1974, 1986; Piotrowska & *al.* 1993; Bishop & Carter 1995, Witczak & *al.* 1994). The European Union Commission suggests that the thickness of a geological barrier should reach at least 3 m, and its permeability coefficient should be $<1\times10^{-9}$ m/s. According to the European Directive, the thickness of the deposits should reach a minimum 1 m, and the permeability coefficient should be equal or smaller than 1×10^{-9} m/s (Wewetzer 2000).

One of the basic criteria for the evaluation of groundwater hazard is the time of vertical migration of the polluting agents from the potential source to the groundwater reservoir (Pleczyński 1988, Kleczkowski & *al.* 1991, Witczak & Żurek 1994). The aim of this paper is to evaluate the influence of lithology, thickness, depth to the groundwater table, infiltration value and concentration of effluents on this process.

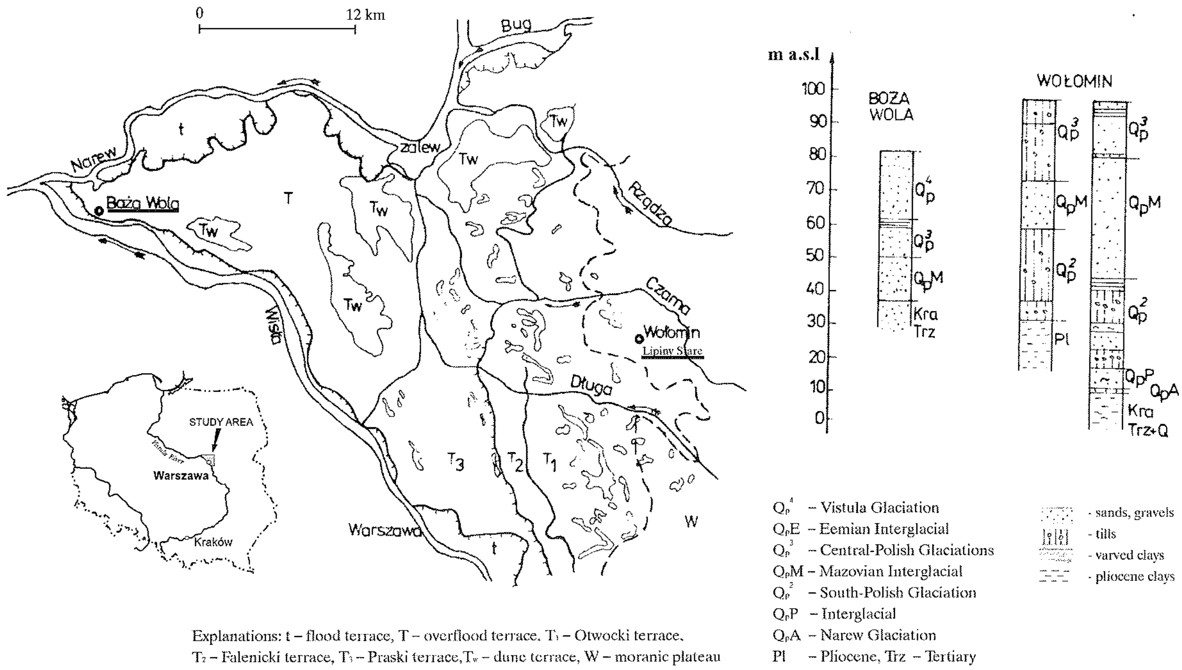

Fig. 1. Geomorphological sketch-map of the north-eastern part of the Warsaw Basin

ANALYSES, METHODOLOGY AND CALCULATIONS

Selection of investigation polygons

The analysis is based on two landfill sites from the eastern Mazovian Voivodship: in the Legionowo district, in the vicinity of Boża Wola; and in the Wołomin district, in the vicinity of Lipiny Stare. These sites were selected because of their different geological-morphological conditions and the lack of any technical protections fulfilling the requirements of environment protection (Złotoszewska-Niedziałek 1995).

The Boża Wola landfill site is located in an abandoned sand and gravel pit within the supra-flood terrace of the Vistula River valley (Text-fig. 1). It covers an area of ca. 0.4 ha, and its body lies 1 to 4 m above the surface. It was opened as a temporary landfill site in 1977. Until 1992 it fulfilled the requirements of a landfill and sewage site for municipal and industrial waste, in which the storage of waste took place without selection. The distance between farmhouses and the landfill site does not exceed 100 m. At present the landfill site is abandoned, covered by a thin soil layer, and overgrown.

The Lipiny Stare landfill site is located on wastelands on a post-Glacial Wołomin Plateau (Text-fig. 1). This is a supra-surface landfill site covering 4.5 ha and ca. 10-12 m high. The landfill site borders to the south a protected forest area, 400 m wide. The site has been used since 1975. Municipal waste and, until 1993, also industrial waste were stored in this site. Until 1993 the exploitation was carried out in a chaotic manner. Currently 5600 m^3/month of municipal waste are stored here.

It should be mentioned that these landfill sites are so-called "wild" landfill sites, i.e., sites selected without any geological, hydrogeological or geotechnical investigations (Złotoszewska-Niedziałek 1998).

Analysis of archival data

The geological, geomorphological and hydrogeological conditions of the study areas are based on the archival data. The hydrogeological cross-sections are the basis for assessing the conception and model structure describing the hydrogeological system.

Geological and hydrogeological setting

To estimate the influence of soil-water conditions on the migration of pollutants in the analyzed sites, the characteristic of the Quaternary deposits and aquifer horizons are crucial.

Boża Wola landfill site: Two aquifer horizons within the Quaternary were recognized (archival data of the State Geological Institute; Malinowski 1991, Nowak 1978). The first horizon is located in deposits of the Eemian Interglacial, Vistulian Glaciation and Holocene. The second one comprises sandy-gravel deposits of the Mazovian Interglacial. The first aquifer horizon is developed as sands and gravels with thicknesses of from a dozen to ca. 40 m (Text-fig. 2), and with a filtration coef-

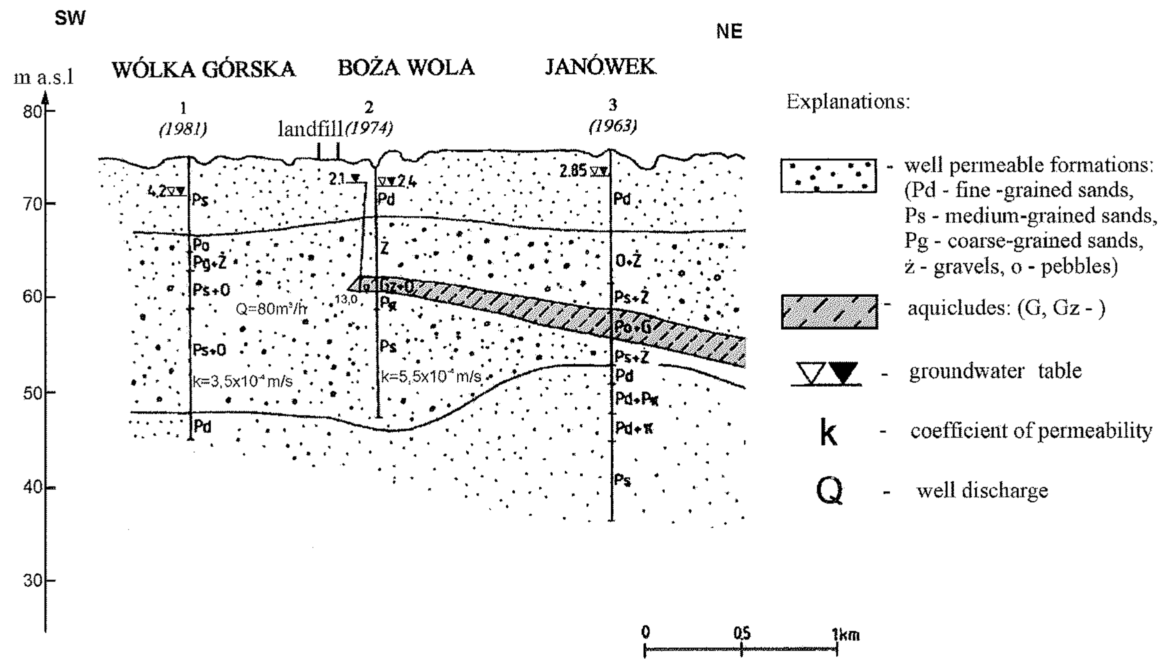

Fig. 2. Schematic hydrogeological cross-section through the supra-flood terrace in the vicinity of the Boża Wola landfill site

ficient (k) between 1.6×10^{-4} and 5.5×10^{-4} m/s. Discharge of the particular exploitation wells varies between 30 and 88 m^3/h. Specific discharges vary between 9 and 30 $m^3/h/1$ m of depression. Waters of the first aquifer horizon have a free water table 3 to 5 m below the surface on the supra-flood terrace. The valleys of the Vistula and Narew rivers are a natural drainage zone for the first aquifer horizon, which is supplied directly from precipitation. Below the first aquifer horizon occur poorly permeable deposits comprising clayey sands, till and clays up to 2-3 m thick, which do not form a laterally continuous complex. The second aquifer horizon is composed of sandy-gravel deposits with thicknesses from a dozen to over 30 m. Waters of this horizon occur in two wells up to 72 m deep, located in Nowy Dwór Mazowiecki. The filtration coefficient for the exploited part of this aquifer varies between 2.3 to 4.9×10^{-4} m/s. Discharge of particular exploitation wells reaches 120 m^3/h. The water table stabilizes at depths similar to the level of the first aquifer water table.

In areas where there is a lack of poorly permeable deposits from the Middle-Polish Glaciations (i.e. the region of the present-day Vistula valley), the second aquifer horizon has a strict hydraulic relation to the higher horizon and both may be treated as a single horizon (ZŁOTOSZEWSKA-NIEDZIAŁEK 1996).

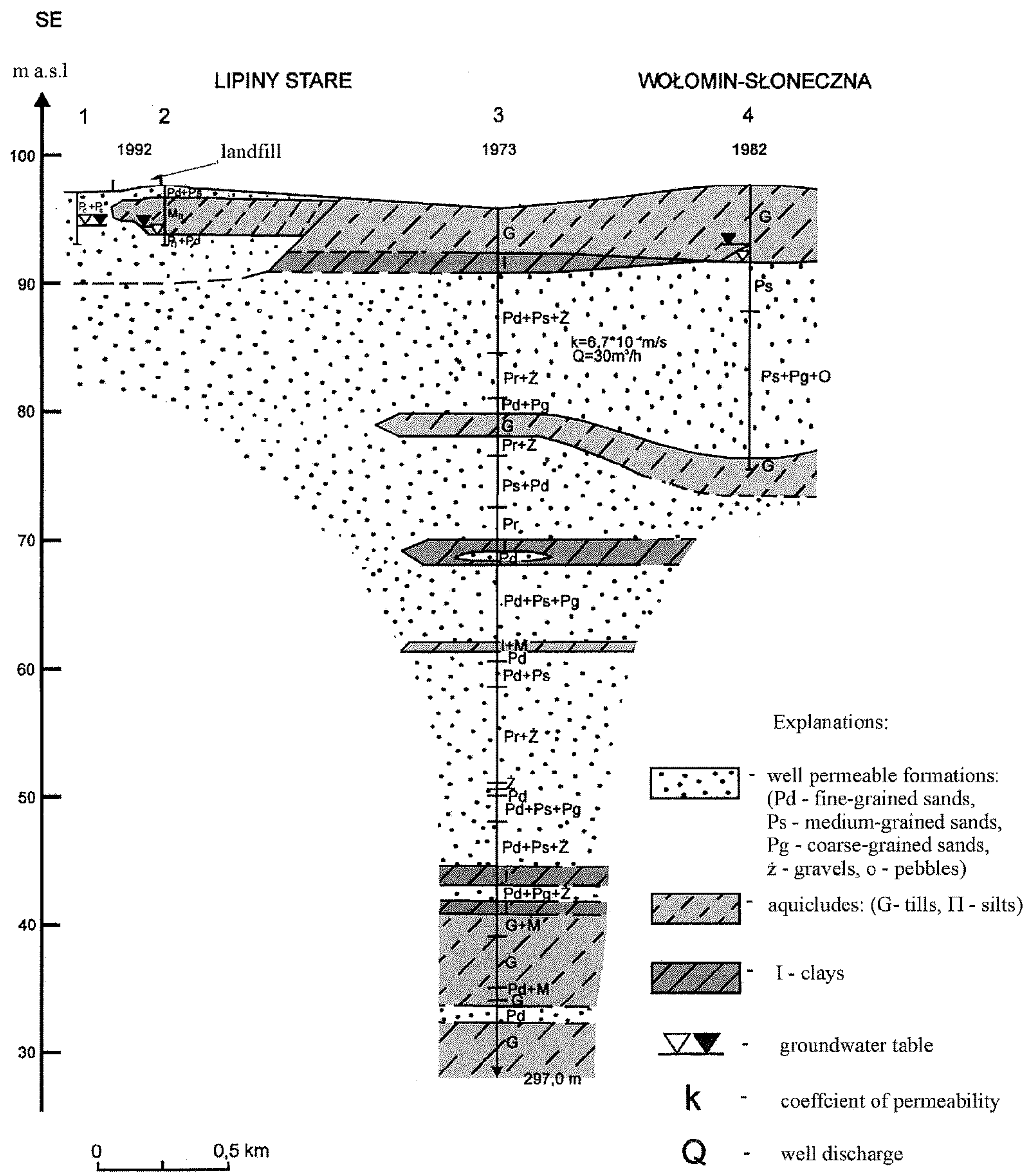

Fig. 3. Schematic hydrogeological cross-section through the plateau in the vicinity of the Lipiny Stare landfill site

Lipiny Stare landfill site: Two continuous aquifer horizons occur in this site (MALINOWSKI & *al.* 1991; NOWAK 1984). The upper horizon comprises fluvioglacial and fluvial sands and gravels of the Middle-Polish Glaciations, with thicknesses of 10-15 m (Text-fig. 3). The permeability coefficient varies between 3.1 and 6.6×10^{-4} m/s, discharges of particular exploitation wells are 45-90 m^3/h, and the specific discharges are 8.5-22.6 $m^3/h/1$ m of depression (archival data of the State Geological Institute). Depending on the isolating deposits the water table of the upper horizon varies and lies at depths of 1.5 to 3.5 m. Groundwater recharge takes place directly through infiltration of precipitation, as well as through lateral inflow from adjacent areas. The first aquifer horizon is underlain by 2-4 m of till, silts and clays. These deposits do not form a continuous cover enabling hydraulic contact of the upper and lower aquifer horizon (e. g. in the vicinity of the water intake for Wołomin). The second aquifer horizon comprises deposits of the Great Interglacial occurring at depths of 20 to 30 m, with thicknesses of between 15 and 30 m. Deposits of this horizon are characterized by a permeability coefficient of 283.3×10^{-4} m/s. The discharge of particular exploitation wells varies between 36 and 108 m^3/h, the specific discharges reach from 9 to 30 $m^3/h/1$ m of depression. Groundwater flows from the SE to the NW (PACZYŃSKI 1995, unpublished data).

Fieldwork and laboratory analyses

The first stage of fieldwork included observations in the vicinity of the selected investigation polygons. Local reconnaissance turned out to be of crucial value in relation to the later analysis of numeric data, because it indicated the presence of additional pollution sources in the vicinity of the investigation polygons (i.e. Benckister plant – chemical plant, leaking cesspools). The second stage of fieldwork included measuring the groundwater table in farm wells and surface flows, as well as collecting water and soil samples for analytical analyses. The detailed location, general data and results of investigations for the particular investigation points were discussed earlier (ZŁOTOSZEWSKA-NIEDZIAŁEK 2001).

Measurements of the groundwater states allowed establishment of the hydrodynamic conditions within the study areas, the determination of the directions of groundwater flow (and thus of the pollutants) and the hydraulic relations with surface waters. Determination of the hydrogeological conditions allowed preparation of the data for future numeric calculations.

Water samples for analysis were taken from selected farm wells, both dug and drilled, and from the River Czarna. A sample of effluents was taken from the girdling ditch. Laboratory analyses included the deter-

Indicator	unit	1996	1999	Permissible values
Colour	mg Pt/dm^3	1730	450	-
Turbidity	mg/dm^3	5	8	-
Reaction	pH	8,11	7.94	6.5 – 9.0
Transmissivity	μS /cm	14170	36670	-
Total hardness	mg $CaCO_3/dm^3$	2220	1091	3500
Oxidability	mg O_2/dm^3	380	261	-
Calcium	mg Ca/dm^3	136	315	-
Iron	mg Fe/dm^3	6	6.83	10
Manganese	mg Mn/dm^3	0.274	0.414	-
Ammonium nitrogen	mg N/dm^3	440	8.77	6.0
Magnesium	mg Mg/dm^3	456,8	72.9	-
Nitrite nitrogen	mg N/dm^3	0.65	0.031	-
Nitrate nitrogen	mg N/dm^3	37	18.2	30
Chlorides	mg Cl/dm^3	6400	6492	1000
Sulphates	mg SO_4/dm^3	1560	763	500
Phosphates	mg PO_4/dm^3	3	2.84	15.3
Zinc	mg Zn/dm^3	0.541	1.93	2,0
Cadmium	mg Cd/dm^3	<0.01	0.008	0.1
Lead	mg Pb/dm^3	0.327	0.093	0.5
Copper	mg Cu/dm^3	0.241	0.071	0.5
Chromium	mg Cr/dm^3	0.196	0.082	0.2
Nickel	mg Ni/dm^3	0.473	0.047	2.0
Mercury	mg Hg/dm^3	<0.001	0.003	0.02
Arsenic	mg As/dm^3	0.015	0.016	0.2

(-) immeasurable quantities

Table 1. Physical and chemical properties of effluent taken from the girdling ditch in the vicinity of the Lipiny Stare landfill site

mination of physical and chemical indicators of surface and groundwater, as well as analyses of soils. The results obtained from the physical and chemical analyses of the groundwater were the basis for evaluating the groundwater quality and its change over time in the study area.

Archival and obtained data indicate that the groundwater in the study area contains macro- and microcomponents in quantities that indicate anthropogenic pollution (ZŁOTOSZEWSKA-NIEDZIAŁEK 2001). Results of the chemical composition analysis for the samples taken from the girdling ditch in Lipiny are presented in Table 1.

Numeric calculations of groundwater flow and pollution transport

Description of the applied software

The dynamics of the migration of pollution in groundwater were described by ANISZEWSKI (1998), BEAR (1987), BURY (1995), DANIEL (1993), MACIEJEWSKI & *al.* (1991), MACIOSZCZYK & SZESTAKOW (1983), MACIOSZCZYK (1994, 1999), SZCZEPAŃSKI (1991), WITCZAK (1994), SZESTAKOW & WITCZAK (1984) and others. Groundwater flow and pollution transport were calculated using FEMWATER software for IBM PC, a computer program worked out by the team of HSIN-CHI J. LIN, GOUR-TSYH YEH, JING-RU CHENG, HWAI-PING CHENG, NORMAN L. JONES AND DAVID R. RICHARDS. This program calculates 3-dimensional modified RICHARD'S equations for groundwater flow using the method of finite elements and equations of mass transport with the use of the LAGRANGE-EULER hybrid method of finite elements. These equations describe pollutants transport in defined boundary conditions.

Flow equations (modified RICHARDS equations):

$$\frac{\rho}{\rho_0}\frac{d\theta}{dh}\frac{\partial h}{\partial t} = \nabla \cdot \left[K \cdot \left(\nabla h + \frac{\rho}{\rho_0}\nabla z \right) \right] + \frac{\rho^*}{\rho_0} q \qquad (1)$$

where: h – pressure head, t – time, K – hydraulic conductivity tensor, z – potential head, q – source and/or sink, ρ – water density at chemical concentration C, ρ_0 – referenced water density at zero chemical concentration, ρ^* – density of either the injection fluid or the withdrawn water, θ – moisture content.

The transport equation was worked out based on laws of mass and flow continuity. These include advection, dispersion/diffusion, adsorption, decay and source/sink.

$$\theta\frac{\partial C}{\partial t} + \rho_b\frac{\partial S}{\partial t} + v \cdot \nabla C = \nabla \cdot (\theta D \cdot \nabla C) - \lambda(\theta + \rho_b S$$

$$+ QC_{in} - \left[\frac{\rho *}{\rho} Q - \frac{\rho_o}{\rho} v \cdot \nabla \left(\frac{\rho}{\rho_o} \right) \right] C \qquad (2)$$

where: θ – moisture concentration, ρ_b – bulk density of the medium, C – material concentration in aqueous phase, S – material concentration in adsorbed phase, t – time, V – discharge, ∇ – del operator, D – dispersion coefficient tensor, λ – decay constant, Q – source rate of water, C_{in} – material concentration in the source.

Hydrogeological schemes in the vicinity of the Boża Wola and Lipiny Stare landfill sites

Boża Wola landfill site: Modelling investigations were carried out on an area of 12.5 km^2. There occurs one isotropic, non-uniform aquifer horizon, continuous horizontally and vertically with spatially distributed streams. Groundwater in the area has a free water table and is drained both by the River Vistula and deeper aquifer horizons. The aquifer horizon is recharged by precipitation as well as by lateral inflow from adjacent areas.

Lipiny Stare landfill site: Numeric calculations were carried out for an area of 11 km^2. There occur two aquifer horizons (isotropic and uniform), continuous vertically and horizontally, separated by poorly permeable deposits. Streams dominated by vertical flow are formed in the poorly permeable horizon. These deposits do not build a continuous complex, therefore a hydraulic contact between the aquifer horizons exists. Groundwater recharge takes place by infiltration of precipitation as well as by lateral inflow from adjacent areas.

Boundary conditions

In order to determine the conditions of a numeric solution the model's boundaries were determined and the corresponding boundary conditions were ascribed, which determined the conditions of exchange of water and mass between the system and its surroundings, as well as the initial conditions.

It was assumed that pollutants flowing into the soil-water environment have the same density and viscosity as groundwater and do not change its character. Pollutants fulfilling these conditions are referred to as passive. It was also assumed that pollutants are stable (conservative). Chlorides were selected as the pollution indicator. This indicator reacts fast and directly to anthropopression, does not undergo transformation during water migration and is sorbed or precipitated from groundwater to a minimal degree (MACIOSZCZYK 1987; MACIOSZCZYK & JEŻ 1995). Increase in the concentration of chlorides in relation to the hydrogeochemical background can be treated as one of the basic indicators of groundwater pollution. Even concentrations lower than the admissible values, but higher than the hydrogeochemical background, typically point to the existence of anthropopression. The models of the numeric grids and the boundary conditions attained are shown in Text-fig. 4.

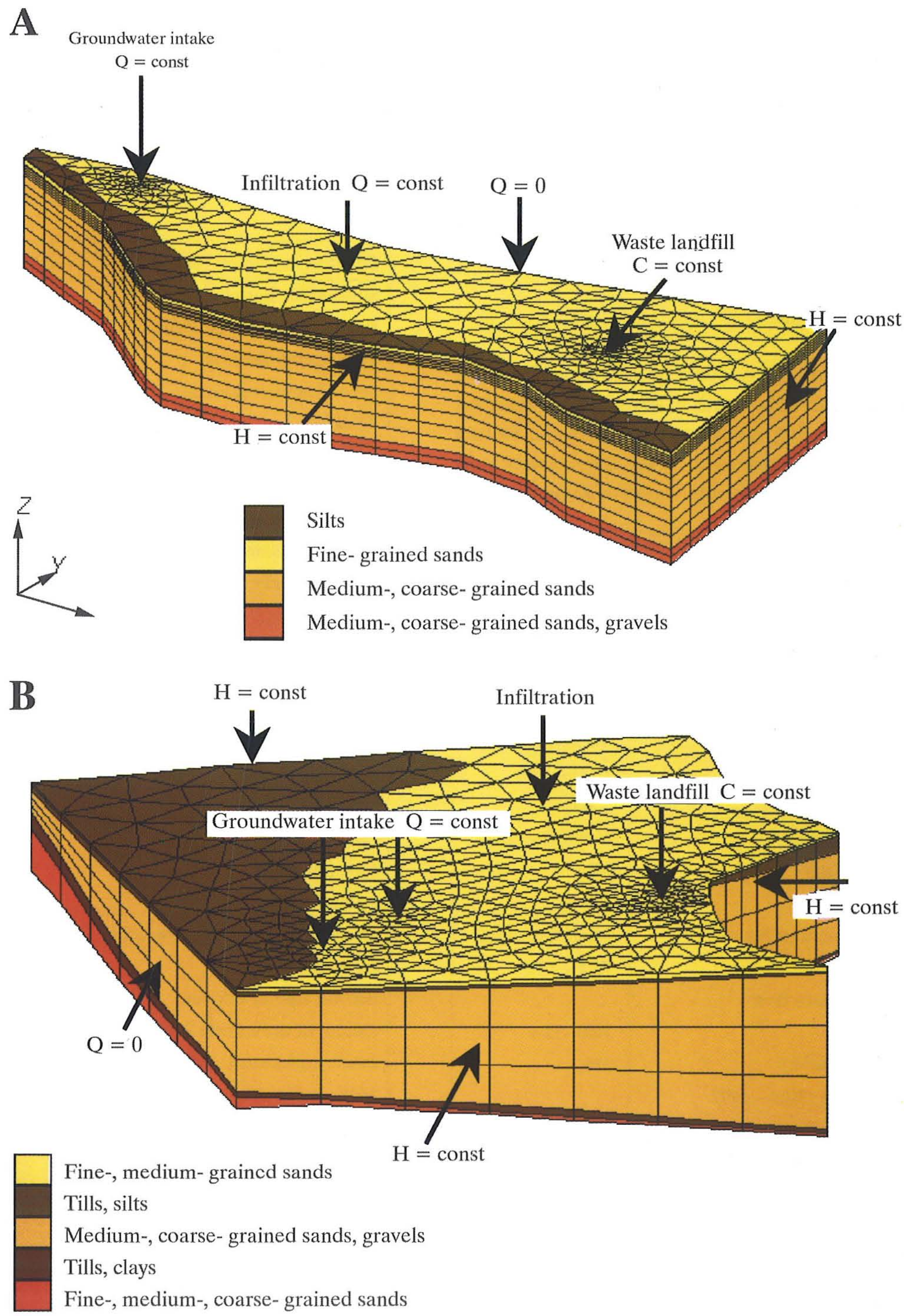

Fig. 4. Model of the numeric grid and the attained boundary conditions for: A) Boża Wola landfill site; B) Lipiny Stare landfill site

Parameters applied to calculations

The data showing the hydrogeological parameters within the study areas (input data for calculations) are presented in Tables 2 and 3. Curves of humidity, transmissivity and water content for zones of incomplete saturation were generated for particular horizons (following CARSEL & PARRISH 1988). Migration parameters were applied from literature data (Table 4). The input data set for constructing the model and for simulation calculation was corrected in the course of model identification.

Due to the poor and uneven recognition of hydrogeological conditions, indicated as the approximate evaluation of aquifer parameters and poorly permeable deposits, the taring method was applied in the identification process (MACIOSZCZYK & KAZIMIERSKI 1990).

Range of calculations

The projection of the local groundwater flow and the mass transport linked with it, as well as the assumed simulations reflecting the influence of particular factors of the soil-water environment on the migration of pollutants, required the following stages of numerical calculations. The first stage included calculations for the groundwater flow. Calculations for the following variants were carried out: simulation I – groundwater flow at zero infiltration; simulation II – groundwater flow at mean infiltration values.

The simulations were focused on determining the model of groundwater circulation and on authenticating the parameter values taken for calculations and determined during laboratory tests or adapted from archival and reference materials. The role of infiltration recharge was evaluated in reconstructing the groundwater circulation by comparing the results obtained from calculations with those measured in the field.

Filtration coefficient [m/s]	Variability range
Sub-surface horizon	**$1x10^{-6}$ – $5.5x10^{-5}$**
Aquifer horizon	**1.1 – 5.0 $x10^{-4}$**
Thickness [m]	Variability range
Sub-surface horizon	**4 – 5**
Aquifer horizon	**70 – 74**
density [kg/m^3]	Variability range
Sub-surface horizon	1600 – 1650
Aquifer horizon	2000
Tortuosity [-]	Variability range
Sub-surface horizon	0.5
Aquifer horizon	0.6 – 0.7
Hydraulic pressure value [m a.s.l.]	Variability range
Aquifer horizon	***71.5 – 73.0***
Datum of the surface flow water table	**70.0 –72.4**
Well exploitation [m^3/h]	**100**
Mean precipitation (1980 – 1997 [mm])	**534**
Infiltration coefficient	0.2 – 0.3
Concentration of polluting substance [mg/dm^3]	1000
Aquifer horizon base datum [m a.s.l.]	**0.0**
Surface level datum [m a.s.l.]	**74.5 – 78.0**

Table 2. Variability range of parameters taken for numeric calculations for the Boża Wola region (input data)

Filtration coefficient [m/s]	Variability range
Sub-surface horizon	***$5.5x10^{-5}$ – $1.4x10^{-4}$***
Poorly permeable deposits	$1x10^{-8}$ – $1x10^{-7}$
First aquifer horizon	**3.1 –$6.7x10^{-4}$**
Second aquifer horizon	**2.0 –$3.3x10^{-4}$**
Thickness [m]	Variability range
Sub-surface horizon	*1- 3*
Poorly permeable deposits (I)	**0.5 – 10**
First aquifer horizon	**16 – 40**
Poorly permeable deposits (II)	**0 – 4**
Second aquifer horizon	**15 –40**
Density[kg/m^3]	Variability range
Sub-surface horizon	1650
Poorly permeable deposits	2000
First aquifer horizon	2000
Second aquifer horizon	2000
Tortuosity [-]	Variability range
Sub-surface horizon	0.5
Poorly permeable deposits	0.7
First aquifer horizon	0.7
Second aquifer horizon	0.6
Hydraulic pressure value [m a.s.l.]	Variability range
First aquifer horizon	***92.0 –97.0***
Second aquifer horizon	**91 – 96**
Datum of the surface flow water table	***92.5 – 97.5***
Intake exploitation [m^3/h]	**300**
Mean precipitation (1982-1997)[mm]	**573**
Infiltration coefficient	0.05 – 0.2
Concentration of polluting substance [mg/dm^3]	1000 – ***6000***
Second aquifer horizon base datum [m a.s.l.]	**32 – 68**
Surface level datum [m a.s.l.]	**95.7 – 99.5**

Table 3. Variability range of parameters taken for numeric calculations for the Lipiny Stare region (input data)

Type of deposit	Longitudinal dispersion constant a_L [m]	Transverse dispersion constant a_T [m]	Author
Fluvioglacial coarse-grained sands and gravels intercalated with fine-grained sands	**21.3***	**4.27***	PINDER (1973)
Fluvioglacial sands and gravels	8.0	-	MAŁOSZEWSKI (1978)
Fluvial sands and gravels	**12*4***	FRIED (1975)	
Fluvial sands and gravels	15	1	FRIED (1975)
Fluvial sands and gravels	30.5	30.5	KONIKOW (1977)

* - parameters taken for calculations

Table 4. Value of dispersion constant according to field analyses (KLECZKOWSKI 1984)

The second stage of calculations includes numeric calculation of the flow and transport of pollutants. This stage was focused on the analysis of the change in time and space of the pollutants concentration (chlorides) in the study areas at the following variable parameters: coefficient of horizons occurring in the landfill site basement, thickness of the aeration zone (depth to water table), infiltration of effluents (quantity) and their concentration.

ANALYSIS OF THE NUMERIC DATA FOR GROUNDWATER FLOW AND POLLUTION TRANSPORT

Analysis of numerical data for groundwater flow in the vicinity of the Boża Wola landfill site

The numerical model focuses on calculating the spatial range of hydraulic pressure for a hydrogeological object, in this case an aquifer horizon with a free water table.

It was assumed that there is a constant vertical inflow, interpreted as a stream of infiltration recharge at a known range of pressures and parameters of the medium. The simulation was carried out assuming a mean precipitation for several years, i.e. 534 mm/year (date of Meteorological and Hydrological Institute) and the infiltration coefficient of 0.3 within the supra-flood terrace and 0.2 within the flood terrace (PAZDRO & KOZERSKI 1991).

Simulation I – calculations were carried out for groundwater flow at zero infiltration, in stable exploitation conditions of the water intake for Nowy Dwór Mazowiecki Q = 100 m^3/h.

Simulation II – calculations were carried out for groundwater flow at stable exploitation Q = 100 m^3/h, including mean values of infiltration I = 0.00043 m/ 24 h (supra-flood terrace) and I = 0.00029 m/ 24 h (flood terrace).

At this stage, the reaction of groundwater on the value of infiltration recharge was tested. Selected numerical data are presented in Text-fig 5. Comparing numeric data, the role of infiltration recharge can be evaluated in reconstructing the scheme of groundwater circulation. As a result of the numerical modelling, the results (in each knot) reflecting the values of hydrostatic pressure, hydraulic head and Darcy's velocity were obtained.

In the vicinity of the Boża Wola landfill site, the groundwater table lies at mean depths between 4.2 and 4.7 m below the surface. The datum of the water table lies at ca. 72 m a.s.l. The velocity of groundwater flow is small and varies between 0.017 and 0.020 m/ 24 h, the hydraulic gradient varies between 0.0006 and 0.0008. The ranges of hydrostatic pressure values are presented on Text-fig. 6. Exploitation of the water intake caused a change in the river's character from draining to infiltrating in the lower course of the River Vistula.

Analysis of numeric data for pollutants flow and transport in the vicinity of the Boża Wola landfill site

Results obtained in the first stage provided the database for numeric calculations of flow and transport of pollutants. The numeric calculations enable evaluation of the concentrations between the measuring points and forecasting the groundwater quality. Results obtained in the numeric modelling method also supplement direct measurements of the concentration of the pollutants, enabling concentrations interpretation during the evaluation of the existing state. This is particularly necessary in those cases where analyses of groundwater quality are sporadic and take place in very few measurement points.

The following variants of numerical calculations were assumed:

– transport of pollutants by advection,
– transport of pollutants by dispersion.

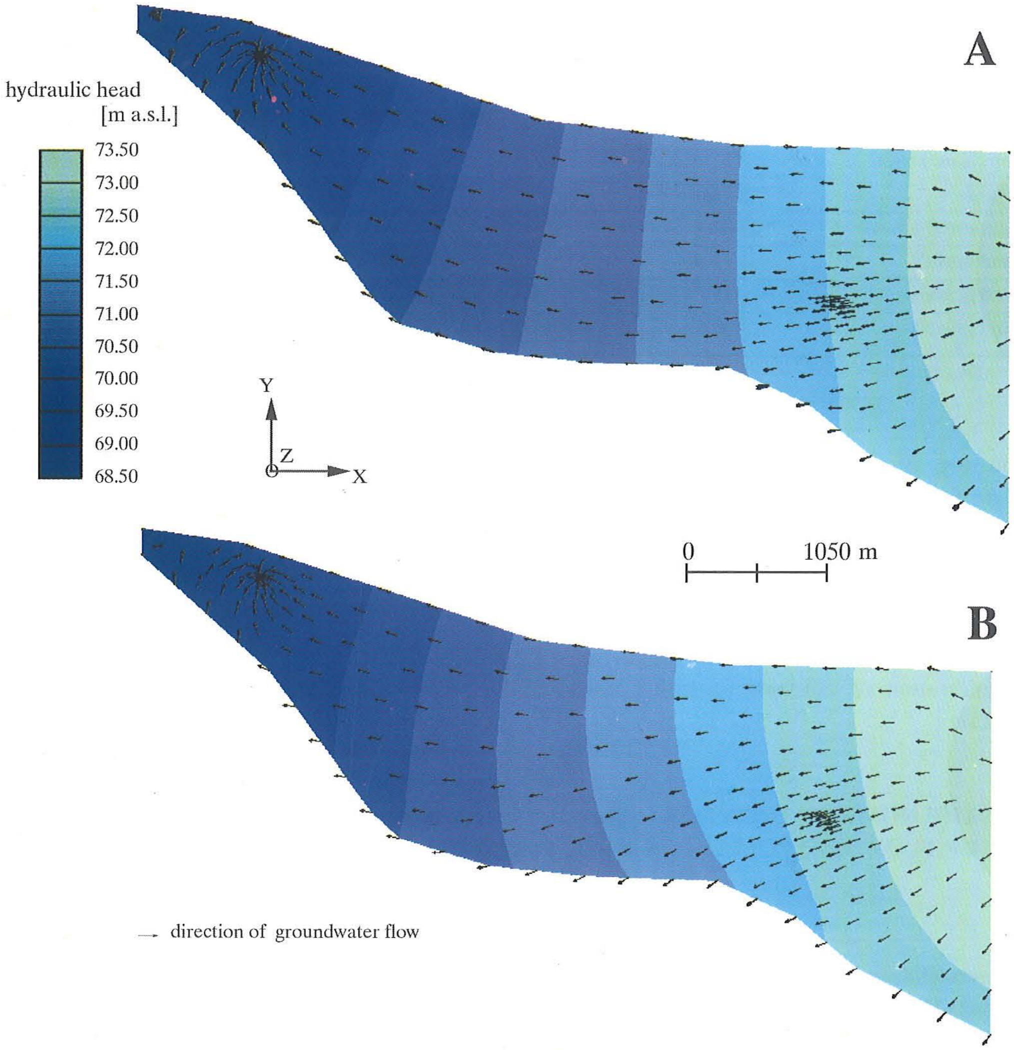

Fig. 5. Range of hydraulic head in the aquifer horizon in the vicinity of the Boża Wola landfill site at A) infiltration = 0; B) including mean values of effective infiltration

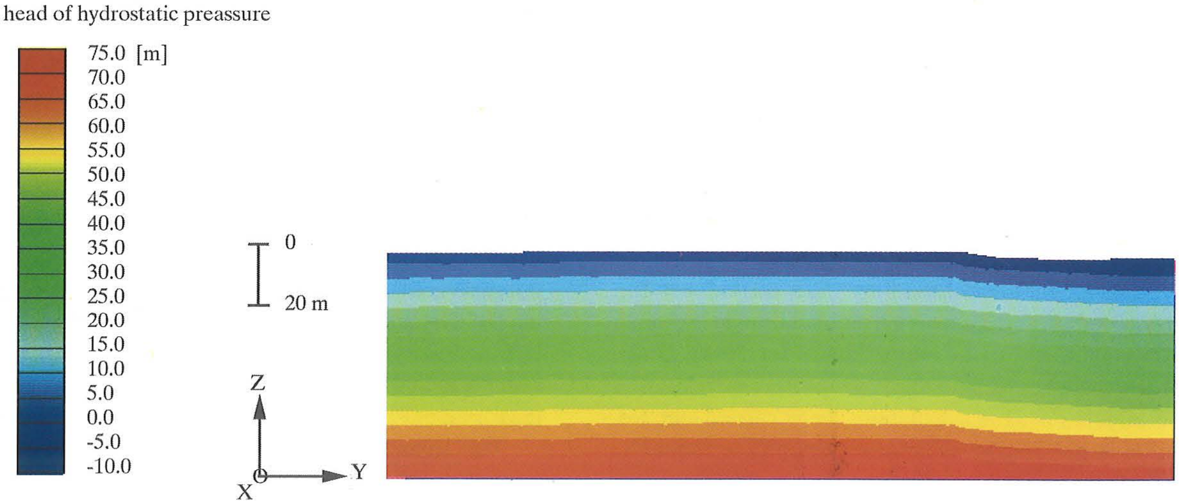

Fig. 6. Range of hydrostatic pressure head values in the aquifer horizon in the vicinity of the Boża Wola landfill site

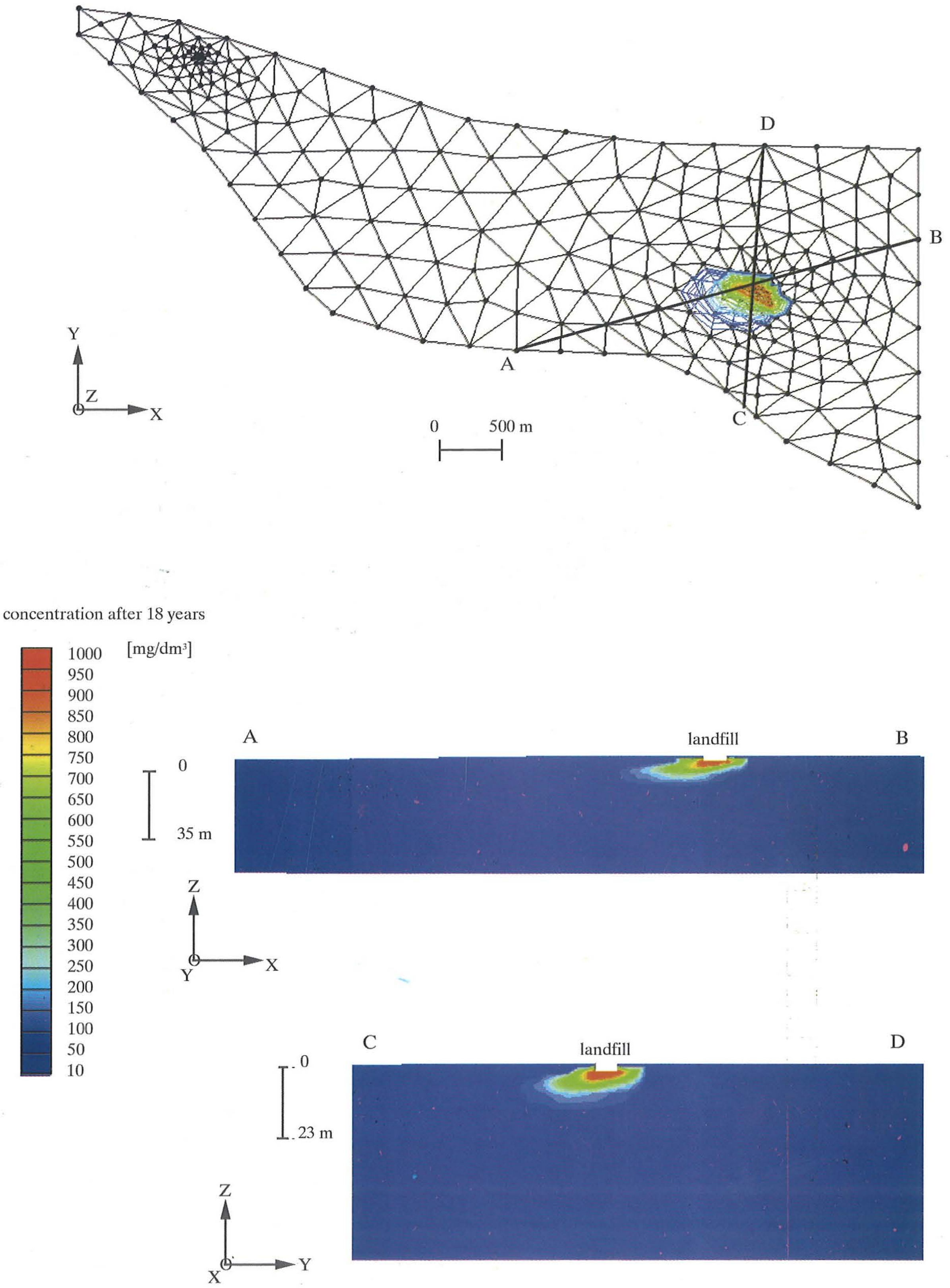

Fig. 7. Distribution of pollutants (chlorides) in time and space in the vicinity of the Boża Wola landfill site (transport by advection)

For the assumed modelling variants, several simulations were carried out, which were focused on the analysis of variability in time and space of the range of chlorine concentrations in the vicinity of the landfill site. The following parameters were taken for calculations: concentration of effluents C = 1000 mg/dm^3, infiltration of effluents I = 0.00043 m/ 24 h (indicator of pollutants condensation – 30%), depth to the groundwater table below landfill site basement – 1.5 m, longitudinal dispersivity a_L – 12m, transverse dispersivity a_T – 4m (Text-figs 7 and 8).

Analysis of the results of the numeric calculations for flow and advectional transport of pollutants indicated that:
- the process of the pollution indicator (chlorine ion) displacement takes place parallel to the direction of the groundwater stream flow, that is towards the river and westwards, with a low velocity of 0.020 m/ 24 h,
- the contamination front (C = 50 mg/dm^3) after 18 years of landfill site exploitation moved from 350 to 450 m towards the river and ca. 370 m westwards,
- the maximal width of the contamination front is 500 m,
- the time when the pollution indicator (chlorides)

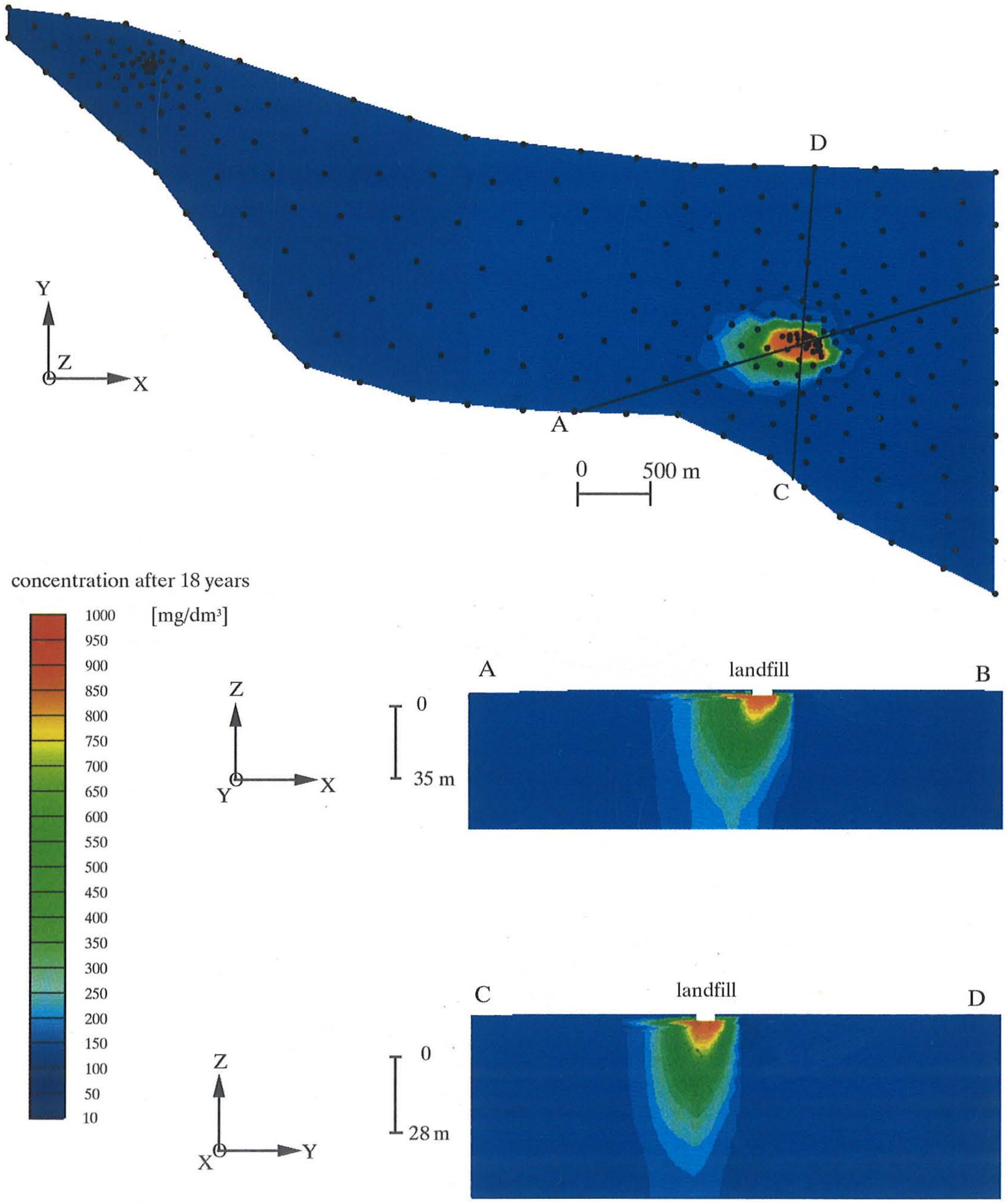

Fig. 8. Distribution of pollutants (chlorides) in time and space in the vicinity of the Boża Wola landfill site (transport by dispersion)

reach the aquifer from the landfill site is 75 days,
- the penetration of pollutants within the soil is 14 m.

Analysis of the results of the numeric calculations of the flow and dispersional transport of pollutants indicated that the contamination front "fades out" horizontally and vertically (Text-fig 8).

Analysis of numeric data for groundwater flow in the vicinity of the Lipiny Stare landfill site

The model calculates the spatial range of hydraulic pressures in a hydrogeological object, in this case a system of two aquifer horizons. The calculations are based on data comprising the parameters of the aquifer horizons and the poorly permeable deposits, the initial and border conditions.

Simulation I – calculations were carried out for groundwater flow at zero infiltration, in stable exploitation conditions of the water intake for Wołomin Q_I = 210 m^3/h, Q_{II} = 90 m^3/h.

Simulation II – calculations were carried out for groundwater flow at stable exploitation, at infiltration I = 0.00031 m/ 24 h for areas, where sandy deposits crop out on the surface and I = 0.00008 m/ 24 h in areas, where tills crop out on the surface.

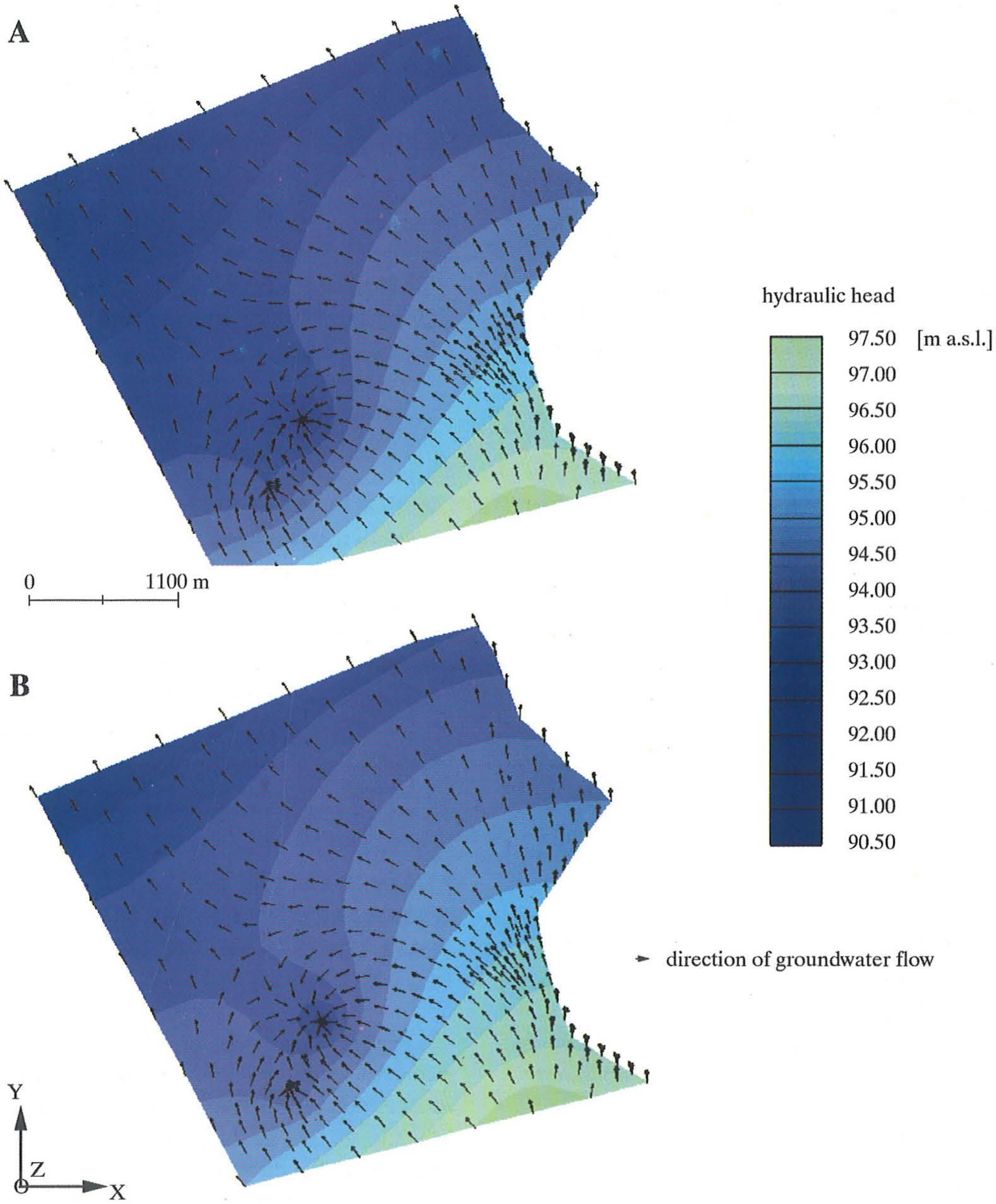

Fig. 9. Range of hydraulic head in the first aquifer horizon in the vicinity of the Lipiny Stare landfill site at A) infiltration = 0; B) including mean values of effective infiltration

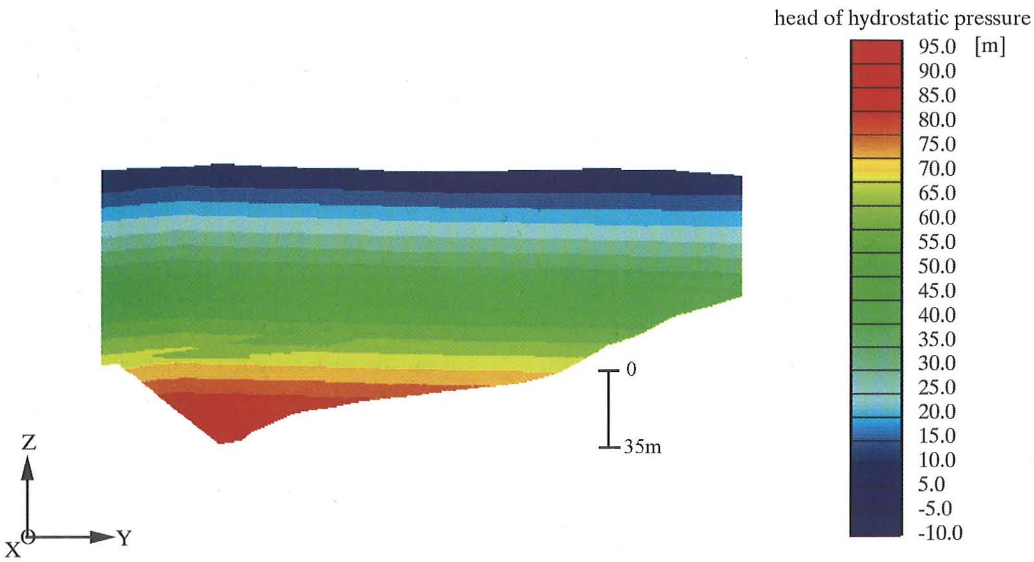

Fig. 10. Range of hydrostatic pressure head values in the aquifer horizon in the vicinity of the Lipiny Stare landfill site

It was assumed that there is a constant vertical inflow, interpreted as a stream of infiltration recharge at a known range of pressures and parameters of the medium. For the simulation mean precipitation for several years, i.e. 573 mm/year (date of Meteorological and Hydrological Institute) and the infiltration coefficient of 0.05 and 0.2 (PAZDRO & KOZERSKI 1990) was assumed.

In the vicinity of the Lipiny Stare landfill site the datum of the groundwater table lies at ca. 95.0 – 95.5 m a.s.l. Groundwater flow is north-westwards (Text-fig 9). Velocity of groundwater flow is low and lies between 0.012 and 0.05 m/ 24 h, the hydraulic gradient varies between 0.0009 and 0.003. The range of the hydrostatic pressure values is presented in Text-fig. 10.

Analysis of numeric data for pollutants flow and transport in the vicinity of the Lipiny Stare landfill site

The following parameters were taken for calculations: infiltration of effluents I = 0.00031 m/ 24 h (indicator of pollutants condensation 0.2), longitudinal dispersivity a_L – 21.4 m, transverse dispersivity a_T– 4.3 m, concentration of effluents C = 6000 mg/dm^3. The results are presented on Text-figs 11 and 12.

The analysis of the results of the numeric calculations for flow and advectional transport of pollutants indicated that:

- the process of the pollution indicator (chlorine ion) displacement takes place parallel to the direction of the groundwater stream flow, that is north-westwards and towards the water intake, with a low velocity of 0.012-0.05 m/ 24 h,
- the contamination front (C = 50 mg/dm^3) after 23 years of landfill site exploitation moved 600 m towards the intake and 700 to 900 m north-westwards,
- the maximal width of the contamination front is 1300 m,
- the time when the pollution indicator (chlorides) reach the aquifer from the landfill site is 0.8 to 4.3 years depending on the thickness and lithology of deposits from the landfill site basement,
- after a 23-year exploitation of the landfill site full saturation of the aquifer horizon by pollutants took place in the vicinity of the site; in the remaining area the penetration did not exceed 25 m of depth,
- a drainage ditch plays a crucial role in the transfer of pollutants; sewage discharge to this ditch is highly hazardous for groundwater.

Analysis of the results of the numeric calculations of the flow and dispersional transport of pollutants indicated that also in this case the contamination front "fades out" horizontally and vertically (Text-fig. 12).

ANALYSIS OF THE INFLUENCE OF SOIL-WATER FACTORS ON THE DISTRIBUTION OF POLLUTANTS IN THE VICINITY OF MUNICIPAL LANDFILL SITES

The presented series of numeric experiments allows evaluation of the influence of particular soil-water factors i.e. deposit thickness, depth to groundwater table, lithology as well as the quantity and concentration of effluents on the dispersion of pollutants in a soil-water environment. Examples of such simulations for selected parameters are presented below.

Boża Wola landfill site: The values of parameters taken

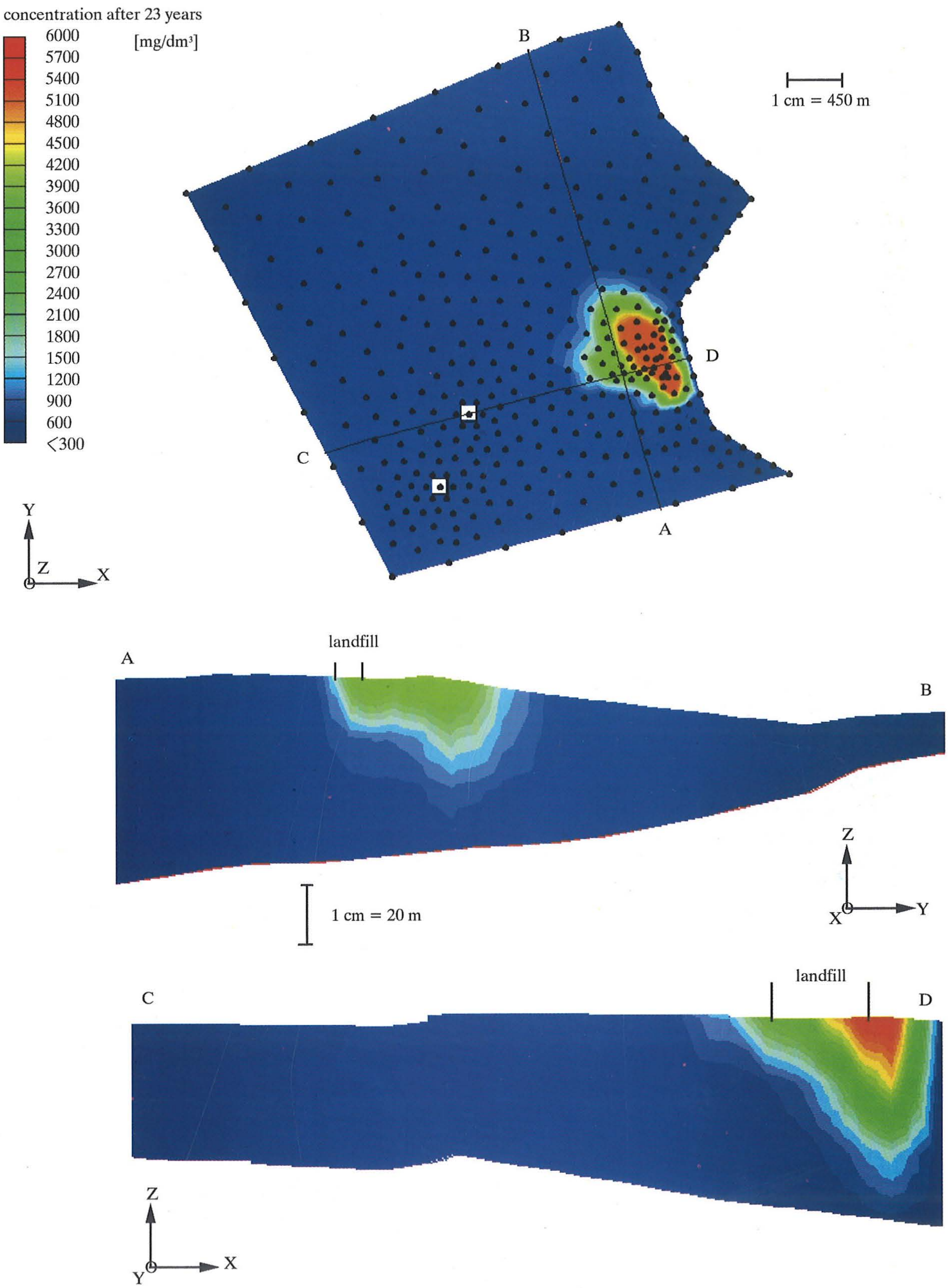

Fig. 11. Distribution of pollutants (chlorides) in time and space in the vicinity of the Lipiny Stare landfill site (transport by advection)

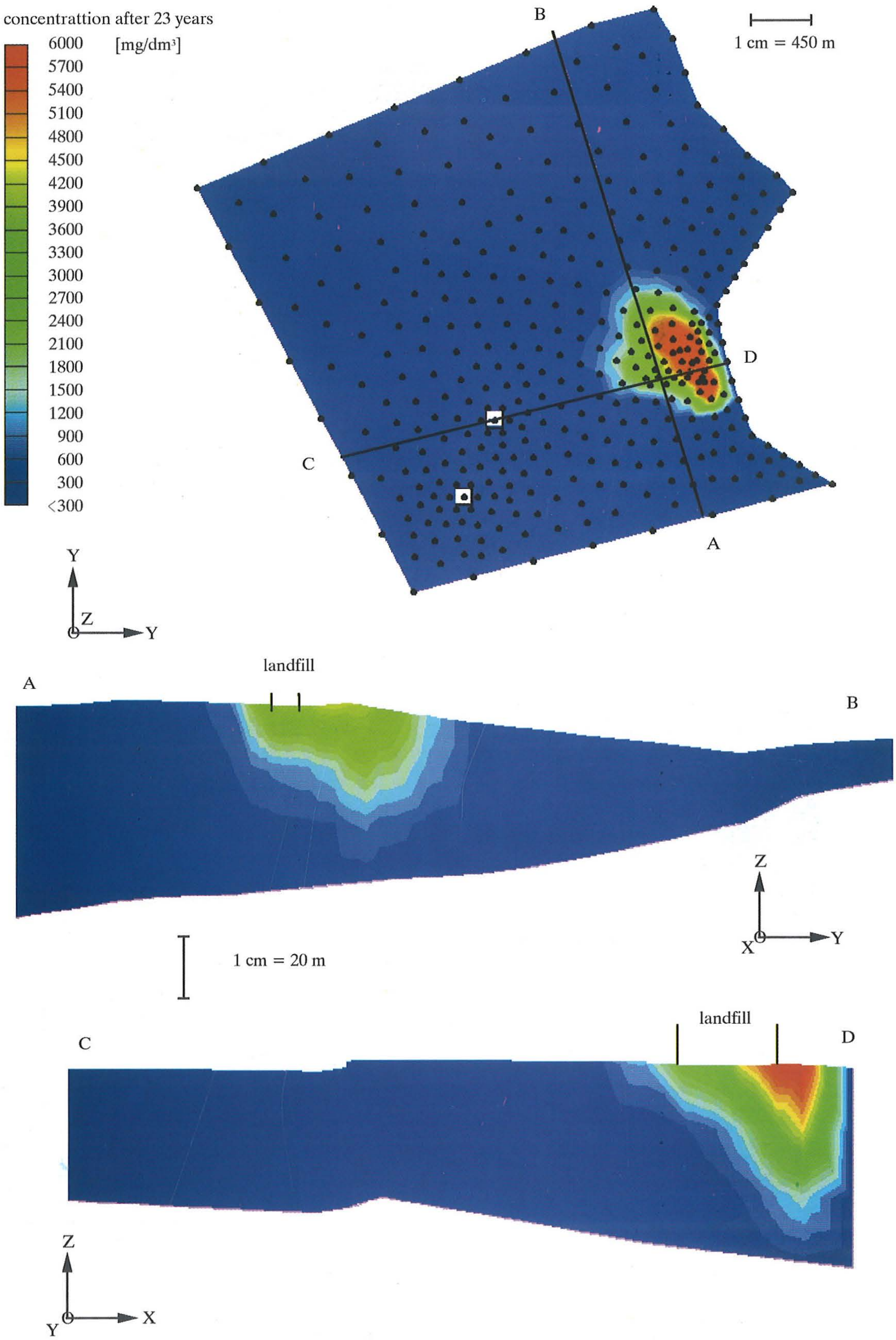

Fig. 12. Distribution of pollutants (chlorides) in time and space in the vicinity of the Lipiny Stare landfill site (transport by dispersion)

for the simulation include:

- thickness of the aeration zone (depth to the groundwater table): 1.5 m, 2.5 m, 3.5 m
- filtration coefficient of the bed lying in the landfill site basement: $k = 2.7\times10^{-4}$ m/s
- infiltration of effluents: $I = 0.00043$ m/ 24 h, $I = 0.00014$ m/ 24 h
- concentration of effluents: $C_1 = 1000$ mg/dm^3.

the conservative substance takes to reach the groundwater table from the pollution source. A two-metre increase caused an almost quintuple increase in the time (at $I = 0.00043$ m/ 24 h).

At $I = 0.00014$ m/ 24 h an increase in thickness of the aeration zone by one metre caused an almost triple increase in the transport time of the conservative substance between the pollution source and the groundwater table.. Under the same conditions, a two-metre increase in thickness caused an almost quadruple increase in the transport time.

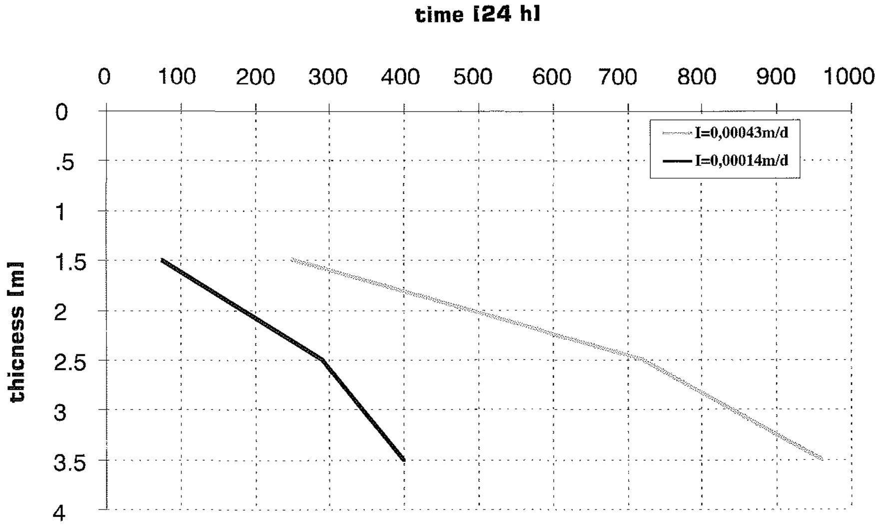

Fig. 13. Influence of the aeration zone thickness on the time taken for pollutants to reach the groundwater in the vicinity of the Boża Wola landfill site

Calculated data showing the influence of the thickness and lithology of deposits in the landfill site basement on the time when pollutants reach the groundwater table are presented in Text-fig 13.

An increase in thickness of the aeration zone by one metre caused an almost quadruple increase in the time

The influence of the infiltration of effluents on the time when the pollutants reach groundwater under particular parameters is shown in Table 5.

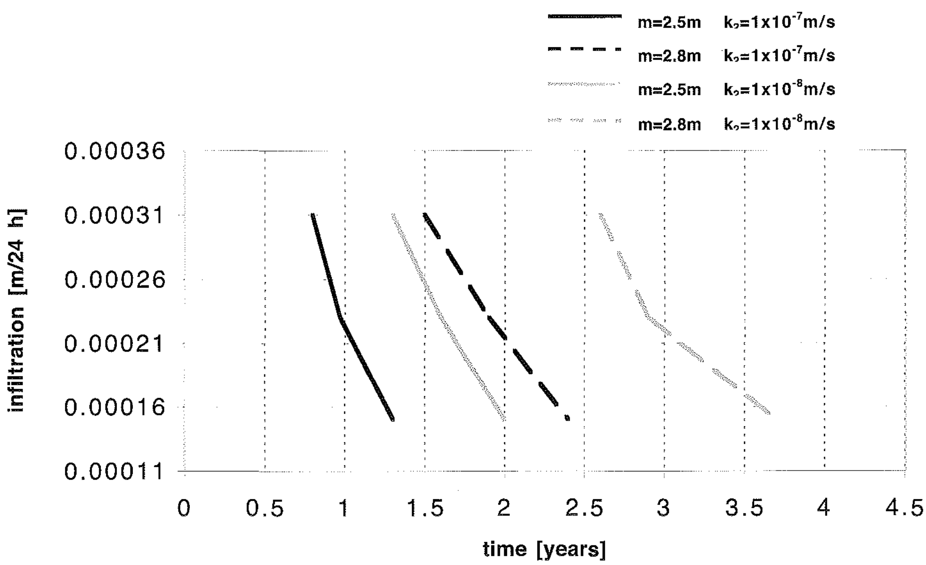

Fig. 14. Influence of the infiltration of effluents on the time taken for pollutants to reach the groundwater in the vicinity of the Lipiny Stare landfill site

Infiltration [m/ 24 h]	Reaching time [m] thickness [m]		
	M = 1.5	M = 2.5	M= 3.5
0.00043	75	290	400
0.00014	250	720	960

Table 5. Influence of the infiltration of effluents on time taken for pollutants to reach the groundwater in vicinity of the Boża Wola landfill site

The infiltration value has a considerable influence on the time taken for pollutants to reach the aquifer environment in the case of shallow groundwater. With depth, the influence of the infiltration value decreases distinctly.

Lipiny Stare landfill site: The different values of parameters taken for the simulation include:

- total thickness of the horizons: 2.5 m, 2.8 m,
- filtration coefficient of the bed lying in the landfill site basement: $k_1 = 1\times10^{-4}$ m/s, $k_2 = 1\times10^{-8}$ and 1×10^{-7} m/s,
- infiltration of effluents: I = 0.00015 m/ 24 h, I = 0.00023 m/ 24 h, I = 0.00031 m/ 24h,
- concentration of effluents: $C_1 = 6000$ mg/dm^3.

Calculated data showing the influence of the thickness and lithology of deposits in the landfill site basement on the time when pollutants reach the groundwater table at a given infiltration (I = 0.00015 m/ 24 h, I = 0.00023 m/ 24 h, I = 0.00031 m/ 24 h) are presented in Tab 6.

The results of the influence of the infiltration of effluents on the time at which pollutants reach groundwater at m = 2.5 and 2.8 m are presented in Text-fig 14.

A twofold decrease in the infiltration of effluents causes a 1.6 times increase in the reaching time (at $k_2 = 1\times10^{-7}$ m/s). When the filtration coefficient of the poorly permeable horizon is 1×10^{-8} m/s, A twofold decrease in the infiltration of effluents causes a 1.5 times increase in the reaching time.

CONCLUSIONS

The composite analysis of the results of investigations and numeric calculations allows the following conclusions to be drawn:

1. Processes of pollution migration in soil within landfill sites are well modelled by the Richards flow equation and mass transport equations. The application of the finite elements method allows reconstruction of the model of groundwater and pollutant circulation in the vicinity of pollution sources, even in a complex geological setting.

2. The numeric calculations of pollution transport in the vicinity of the investigated landfill sites indicate that the dominating element of transfer is convection transport at a low participation of molecular diffusion processes, and the distribution of concentrations at their transportation front is a result of hydrodynamic dispersion.

3. The process of pollution transfer depends to a variable degree on soil-water factors occurring in the landfill site basement. The calculations confirm that, in the case of a basement composed of well permeable deposits, the main factor influencing the time taken for pollutants to reach the groundwater environment is the depth to the water table (thickness of the aeration zone).

4. The calculations confirm that the value of infiltration also plays a large role on the time taken for pollutants to reach the groundwater environment. In the case of a landfill site basement composed of well permeable deposits, a triple decrease in infiltration causes a 2.5 to 3 times increase in the reaching time. In the case of a landfill site basement composed of permeable deposits underlain by poorly permeable deposits, a twofold decrease in infiltration causes a 1.2 to 2 times increase in the reaching time.

5. The calculations indicate that the next factor influencing the reaching time is the concentration of efflu-

Thickness [m]	Filtration coefficient [m/s]	Reaching time [years]		
		I = 0.00031 [m/ 24 h]	I = 0.00023 [m/ 24 h]	I = 0.00015 [m/ 24 h]
$M_1 = 0.8$ $M_2 = 1.7$	$k_1 = 2.7\text{x}10^{-4}$ $k_2 = 1\text{x}10^{-7}$	0.8	1.0	1.3
	$k_1 = 2.7\text{x}10^{-4}$ $k_2 = 1\text{x}10^{-8}$	1.3	1.6	1.9
$M_1 = 0.8$ $M_2 = 2.0$	$k_1 = 2.7\text{x}10^{-4}$ $k_2 = 1\text{x}10^{-7}$	1.5	1.9	2.4
	$k_1 = 2.7\text{x}10^{-4}$ $k_2 = 1\text{x}10^{-8}$	2.6	2.9	3.7

Table 6. Influence of thickness and lithology of deposits from the Lipiny Stare landfill basement on the time taken for pollutants to reach the groundwater, at different infiltration values

ents, as a 6-times increase in their concentration causes an average 2.5-times decrease in the reaching time.

6. The presented methodology of evaluating the influence of non-isolated landfill sites on the environment using numeric modelling requires detailed documentation of the geological setting in the study area.

7. The analyses and numeric calculations indicate that further investigations of pollution transport in a soil environment should include the parameters of flow rate and migration, the values of which depend on the stage of pollution accumulation in soil.

Acknowledgments

The final version of this paper benefited greatly from thorough reviews by Prof. A. DRĄGOWSKI, Warsaw, and Dr. G. BARCZYK, Warsaw.

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Manuscript submitted: 10th February 2003
Revised version accepted: 20th April 2004