IMPROVED HYDROGEOLOGICAL MODEL FOR EVALUATING CONTAMINANT MIGRATION IN GROUNDWATER POLLUTED BY SULPHUR – SLUDGE POOLS AT INCUKALNS, LATVIA

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1 INTRODUCTION

From 1956 to 1981, the Oil Processing Factory of Riga created annually about 16,000 tonnes of highly toxic waste. This sludge consisted of tar, asphalthens, H_2SO_4, sulphuric acids and other hazardous substances. The waste was discarded into two abandoned sand – pits located at the Incukalns village. The pits become waste pools, each covering about 1.3 ha. The pools were informatively named the Northern and Southern ones, which were formed during 1956 – 1965 and 1964 – 1981, accordingly(Aleksans et al., 1993). In 2005, the pools still acted as hazardous contamination sources and their pollution plumes were expanding.

The waste from the pools leaked downward from the sandy Quaternary aquifer *Q* into the Devonian sandstone aquifer *D3gj2*. There dissolved waste components were migrating downgradient towards the Gauja river. Fortunately, for both pools, contaminated areas of the *Q* aquifer now are limited and practically motionless. In centres of the still expanding plumes of the *D3gj2* aquifer, Ph is 3 – 4, SO_4 and surface active components (SAC) reach 4,500 mg/l and 100 mg/l, respectively.

The plume of the Northern pool is approaching the Gauja river and will reach it after ~ 25 years.

In 1998, a hydrogeological model (HM) for the contaminated Incukalns place has been created and rough prognoses of SO_4 and SAC migration have been obtained (Spalvins et al., 1999). In 2004 – 2005, this HM has been considerably improved, in order to find the best methods of stopping pollution plumes and of lessening their impact on local environment. In the paper, improved HM is described and new results obtained are presented.

2 DESCRIPTION OF HYDROGEOLOGICAL MODEL

The HM (version 1998) covered the 8 km × 12 km area (Fig. 1). The model accounted for four aquifers (*Q*, *D3am*, *D3gj2*, *D3gj1*) and two boundary condition surfaces (the maps of landscape elevations ψ_{rel} and the fixed head distribution ψ_{D2ar} of the *D2ar* aquifer) on the HM top and bottom, respectively. Formally, the maps ψ_{rel} and ψ_{D2ar} also represented aquifers. These six aquifers were separated by five aquitards (*aer*, *gQ*, *D3gj2z*, *D3gj1z*, *D2br*) where the *aer* aquitard was a formal substitute of the unsaturated aeration zone. On the four vertical sides of HM, the piezometric boundary conditions were specified.

The REMO system (Spalvins et al., 1996) was used for creating and calibration of HM. The final results provided Groundwater Vistas (GV) system (Environmental Simulation, 2003).where the MODFLOW model supported HM. Contamination migration prognoses were obtained by the MT3D’96 code as a part of the GV system.

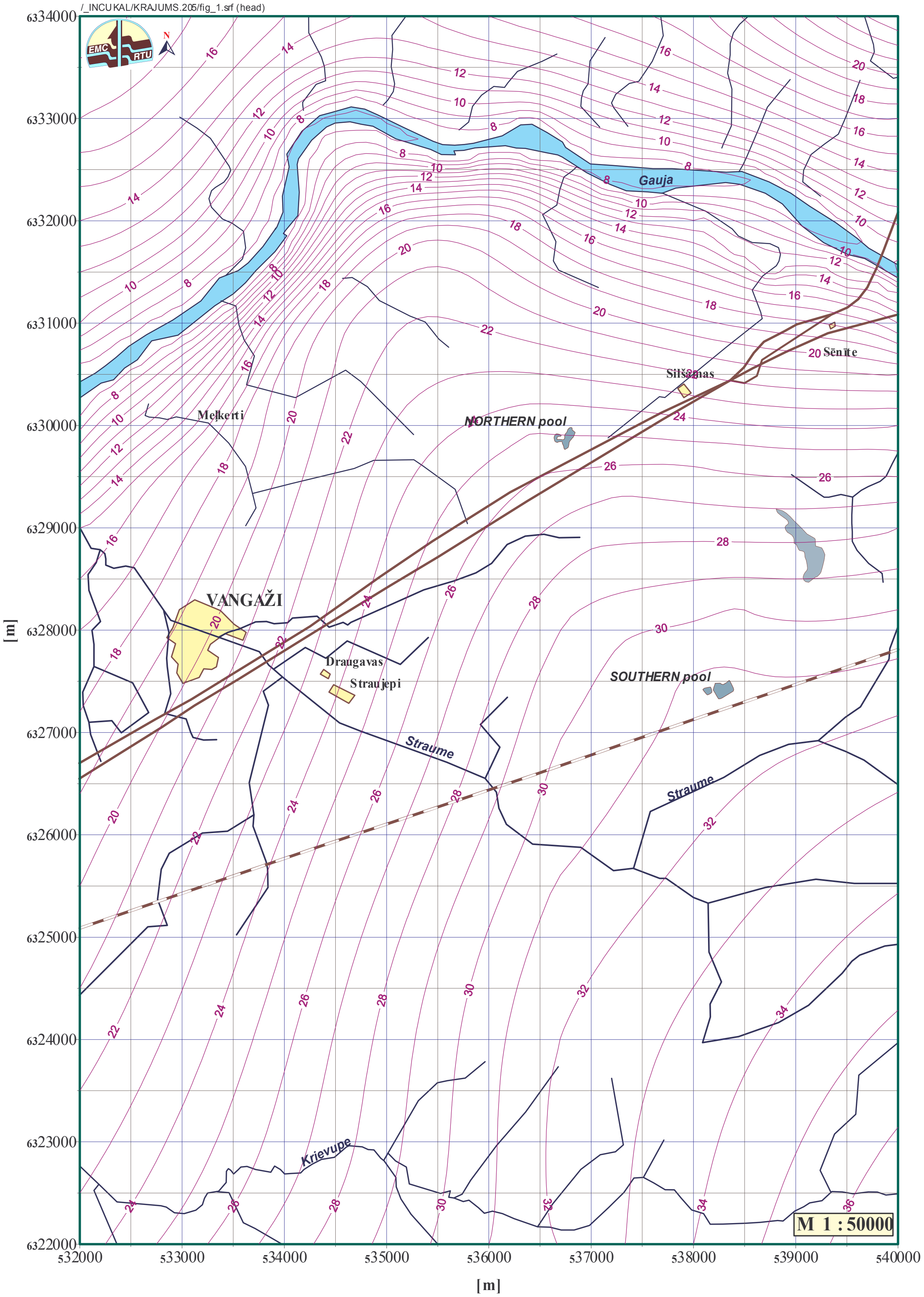


Fig. 1. Layout of the hydrogeological model for the Incukalns place. Distribution of piezometric levels [m asl] of the $D_3 gj2$ aquifer

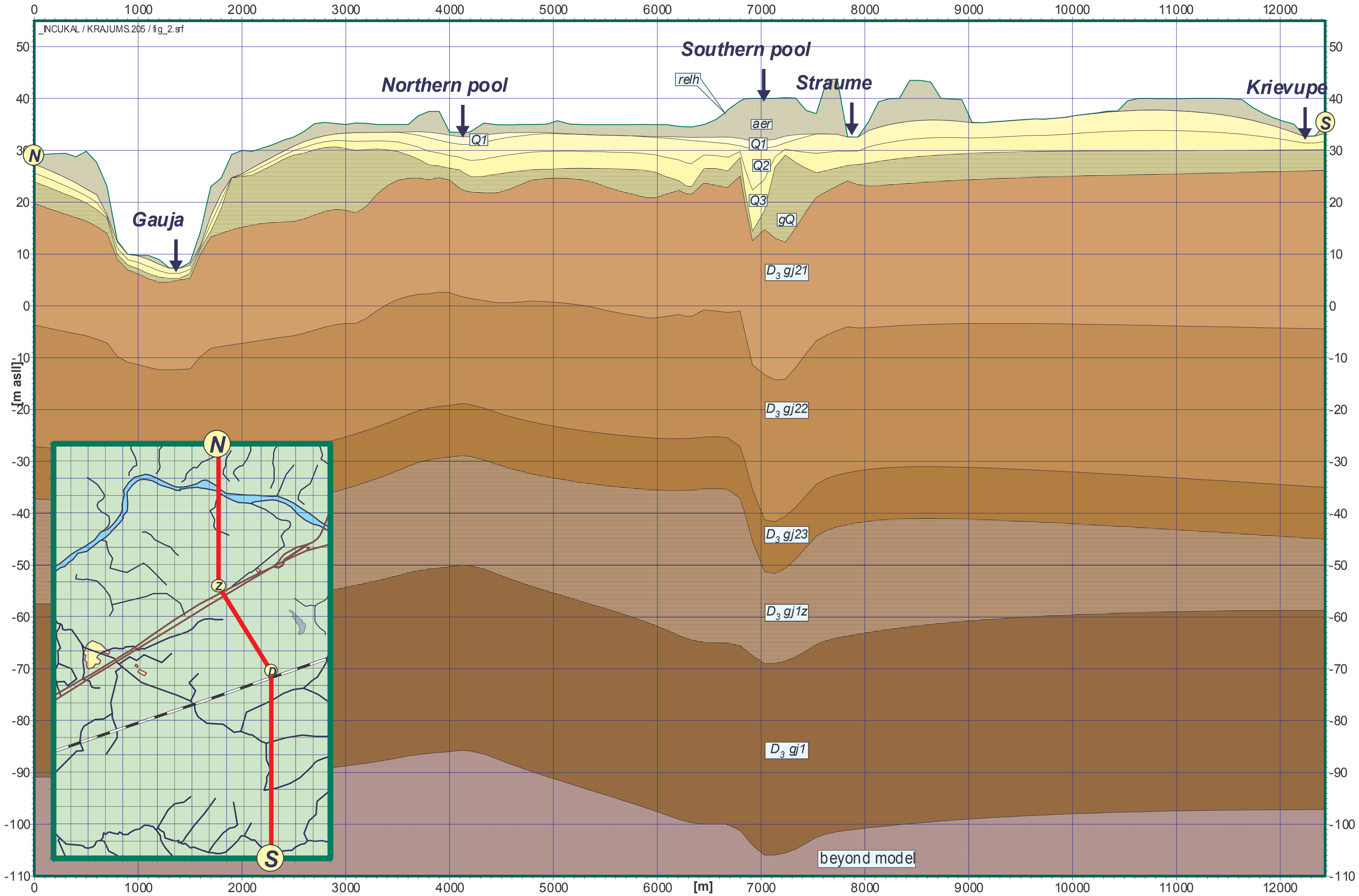


Fig. 2. The geological cross section N_S drawn through the Northern and Southern pools

Although, the basic HM provided valuable results, the following drawbacks, regarding contaminant migration modelling, were discovered:

- it was impossible to account for three dimensional (3D) nature of contaminant migration in the *Q* and *D3gj2* aquifers, because they were represented in HM only by one grid plane each.
- in MT3D'96, the quasi – 3D scheme was used for approximation of contaminant transport processes; for this reason, the MT3D'96 code was not able to provide quite correct results, because the more complex 3D scheme was not applied;
- the MT3D'96 code included a lot of errors and it also was not able to provide results for time periods longer then 15,000 days.

Improved HM (version 2005) was built by using main parameters (area, approximation step, geometry of strata) of basic HM. The following necessary changes were made:

- to account for 3D – nature of contaminant migration, the *Q* and *D3gj2* aquifers were divided in the three subaquifers Q_1, Q_2, Q_3 and *D3gj21*, *D3gj22*, *D3gj23*, correspondingly (Fig. 2);
- the *D3am* and *D2ar* aquifers were excluded from HM, because the *D3am* aquifer was nonexistent in areas of the waste pools and the *D2ar* aquifer had small impact on contaminant migration processes; therefore, the bottom surface of the D3gj1 aquifer was set impermeable;
- a variable thickness for the *aer* zone was used instead of the constant one applied in basic HM;
- accuracy of permeability maps of geological strata was improved and boundary conditions of the HM edges were adjusted, in order to obtain concurrence of migration trends for modelled and observed pollution plumes;
- in GV, the 3D approximation scheme was used and the considerably better MT3D'99 code (Zheng, 1998) was applied.

Main tasks to be solved by the improved model were, as follows:

- to evaluate current parameters for SO_4 and SAC components of contamination plumes of the *D3gj2* aquifer;
- to obtain contamination migration prognoses for the worst case when no sanitation will be attempted;
- to test effectiveness of various sanitation methods.

Three main sanitation methods were considered:

- withdrawal from the *D3gj2* aquifer of polluted groundwater, its cleaning and reinfiltration into the aquifer;
- blocking of the infiltration flow for the pool areas, in order to reduce the waste dissolution rate;
- excavation of the waste pools.

For improved HM, local HM (plane approximation step 20 metres) for the both pool areas also were created. However, these HM were not used in the reported investigation stage.

3 CURRENT PARAMETERS OF CONTAMINATION PLUMES

Current parameters (year 2005) were obtained by using observed concentration distributions of SO_4 and SAC as initial data. For SO_4, its stratification under impact of gravity was accounted for by specifying initial concentrations in the subaquifers *D3gj21*, *D3gj22*, *D3gj23* at ratios 0.7:1.0:2.0, accordingly. For SAC, the concentrations at these subaquifers were equal. In Fig. 3, the observed SO_4 concentrations are shown for the *D3gj22* aquifer. It was assumed that contours of SO_4 and SAC plumes coincided. The value 0.27 of porosity was applied. No sorption of SO_4 and SAC was accounted for. There was no destruction of SO_4. For SAC, the half life time value $t_{0.5} = 15$ years was used to account for destruction of this substance.

The track of contaminant migration versus time were obtained by the MODPATH system (part of GV). Areas and water volumes of contaminant plumes were computed by using the SURFER system (Golden Software, 1997).

In Table 1, the current parameters (year 2005) for the SO_4 and SAC plumes are summarized. The following conclusions can be driven from considering these data:

- the plumes of the Northern and Southern pools will reach the Gauja river after 25 and 65 years, accordingly; since 2005, the Northern pool plume will move faster, due to the enlarged hydraulic gradient of the groundwater flow in vicinity of the river (Fig. 1);
- the geometrical parameters of both plumes are almost equal: the area ~ 150 ha, the volume ~ $18 \cdot 10^6$ m^3;
- the mass of SO_4 for the Southern pool plume is larger than for the Northern one ($24.8 \cdot 10^6$ kg > $9.1 \cdot 10^6$ kg) because the mean outflow of SO_4 for the Southern pool is larger (1700 kg/day > 500 kg/day);
- the mean concentration of SO_4 (500 – 1300) mg/l exceeds (3.3 – 8.5) times the allowed value 150 mg/l for drinking water;
- the mean concentration of SAC (6 – 7) mg/l is much larger (325 times) than the allowed one 0.02 mg/l for drinking water.

Table 1. Current parameters (year 2005) for the SO_4 and SAC plumes in the *D3gj2* aquifer

Nr.	Parameters	Northern pool	Southern pool
1.	existence time of pool [years]	50	40
2.	after what time will contamination reach Gauja river [years]	25	65
3.	mean migration speed till 2005 [m/year]	28	44
4.	mean migration speed from 2005 till 2030 [m/year]	50	46
5.	contaminated area [ha]	148	139
6.	volume of contaminated groundwater [m^3]	$17.65 \cdot 10^6$	$18.73 \cdot 10^6$
7	mass of SO_4 [kg]	$9.1 \cdot 10^6$	$24.8 \cdot 10^6$
8.	mean concentration of SO_4 [mg/l]	515	1320
9.	mean outflow of SO_4 from pool [kg/day]]	500	1700
10.	mass of SAC [kg]]	$1.06 \cdot 10^5$	$1.31 \cdot 10^5$
11.	mean concentration of SAC [mg/l]	6	7
12.	mean outflow of SAC from pool [kg/day]]	18	20

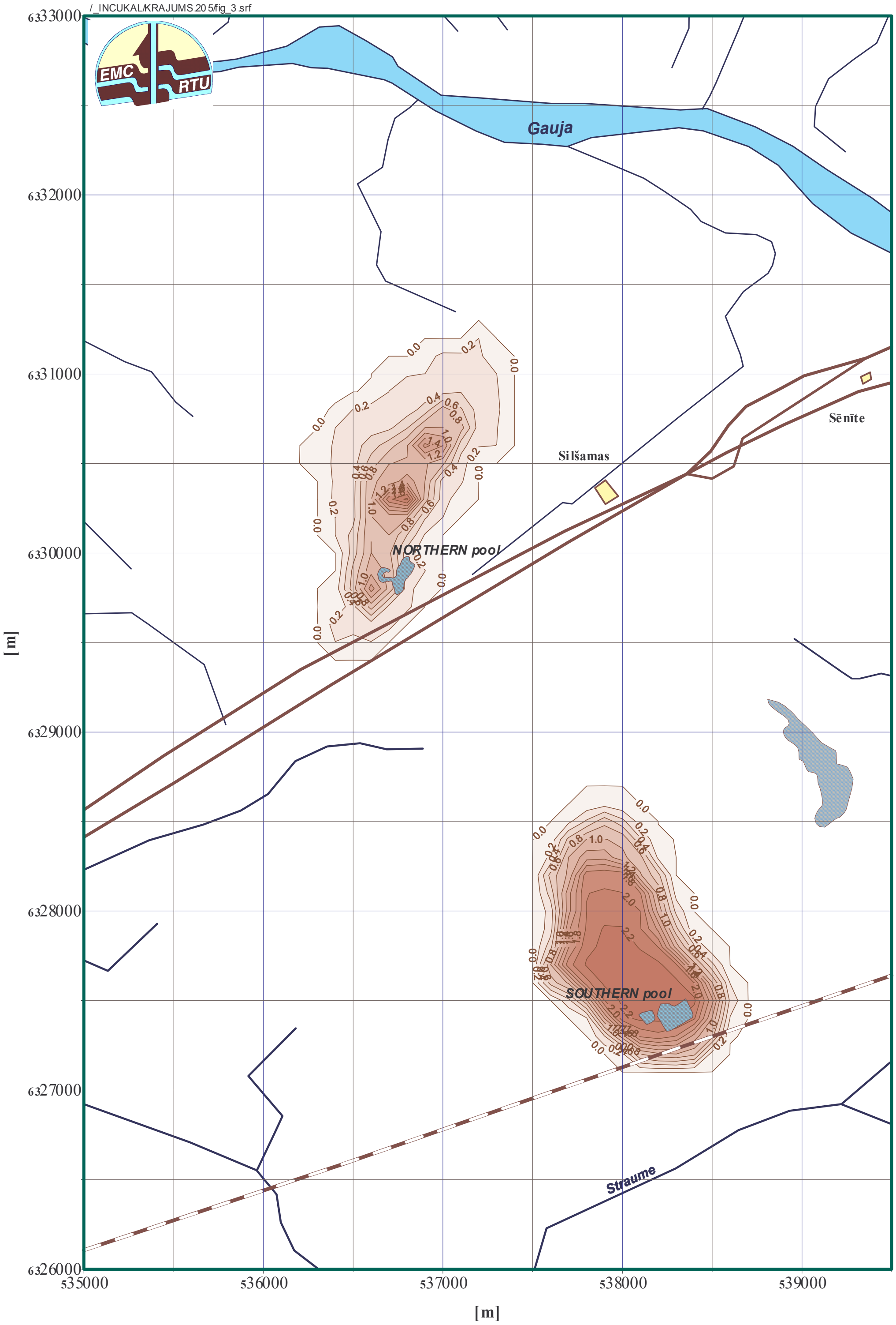
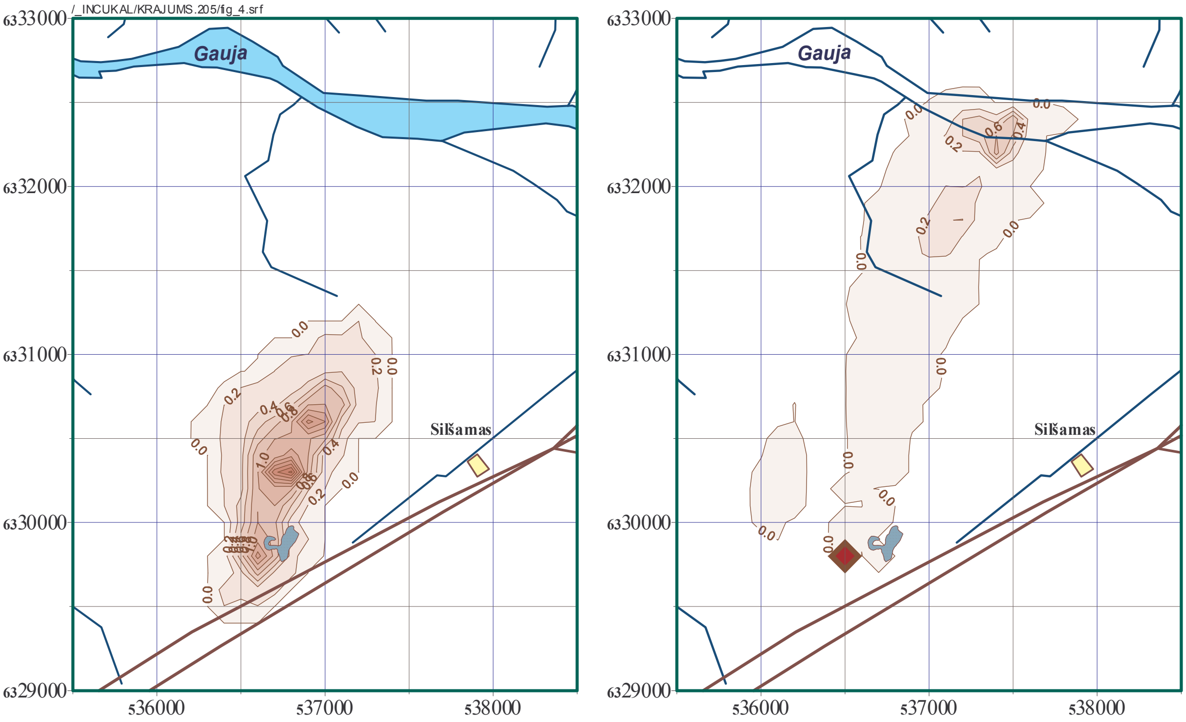
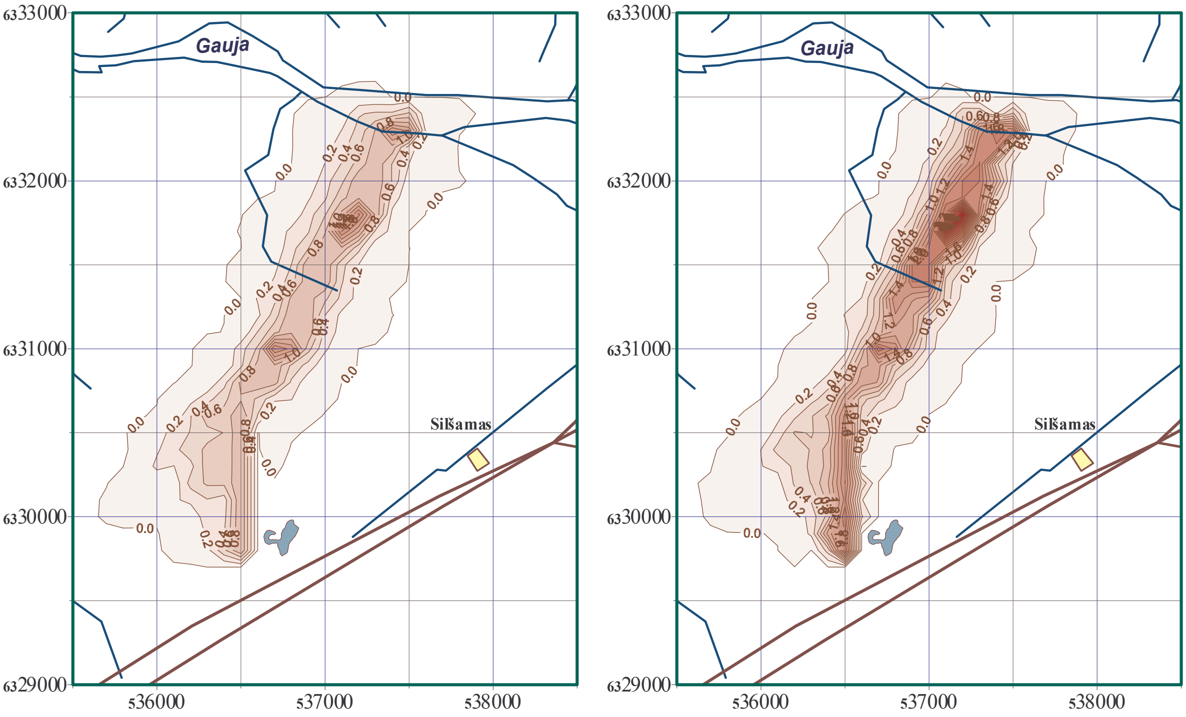


Fig. 3. Distributions of SO_4 concentrations [g / l] for the D_3gj22 subaquifer of the Northern and Southern pool plumes in 2005

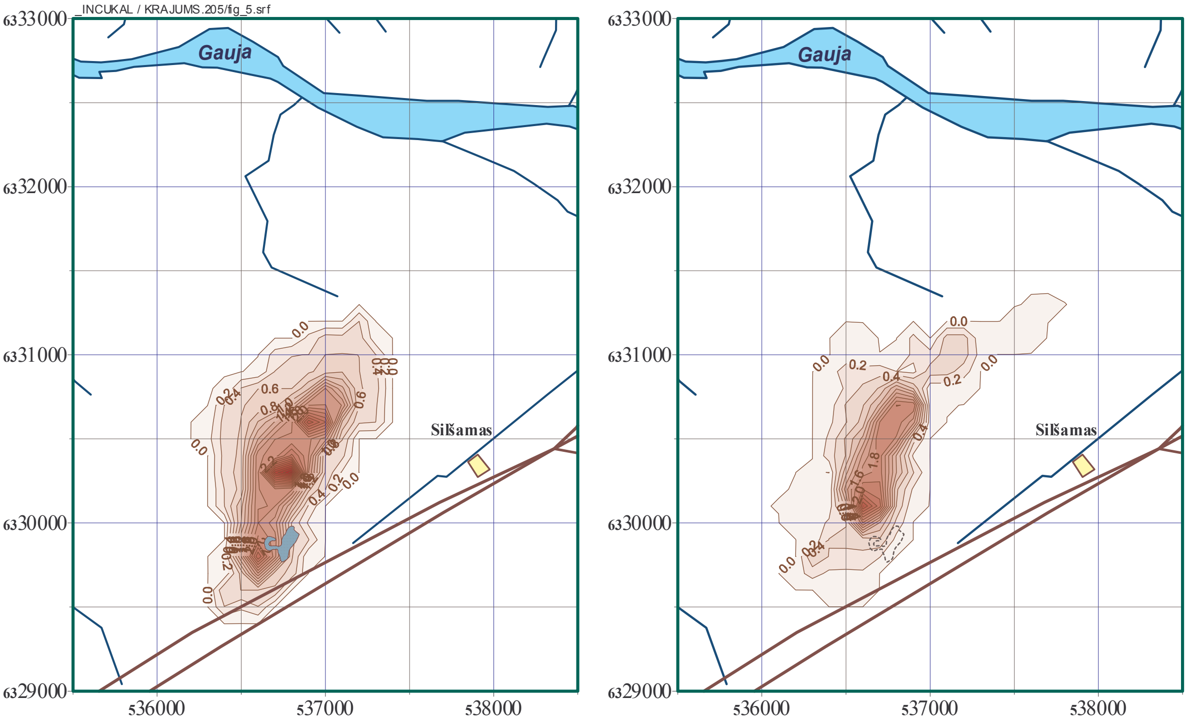


a) year 2005 D_3gj22 b) year 2045 D_3gj21

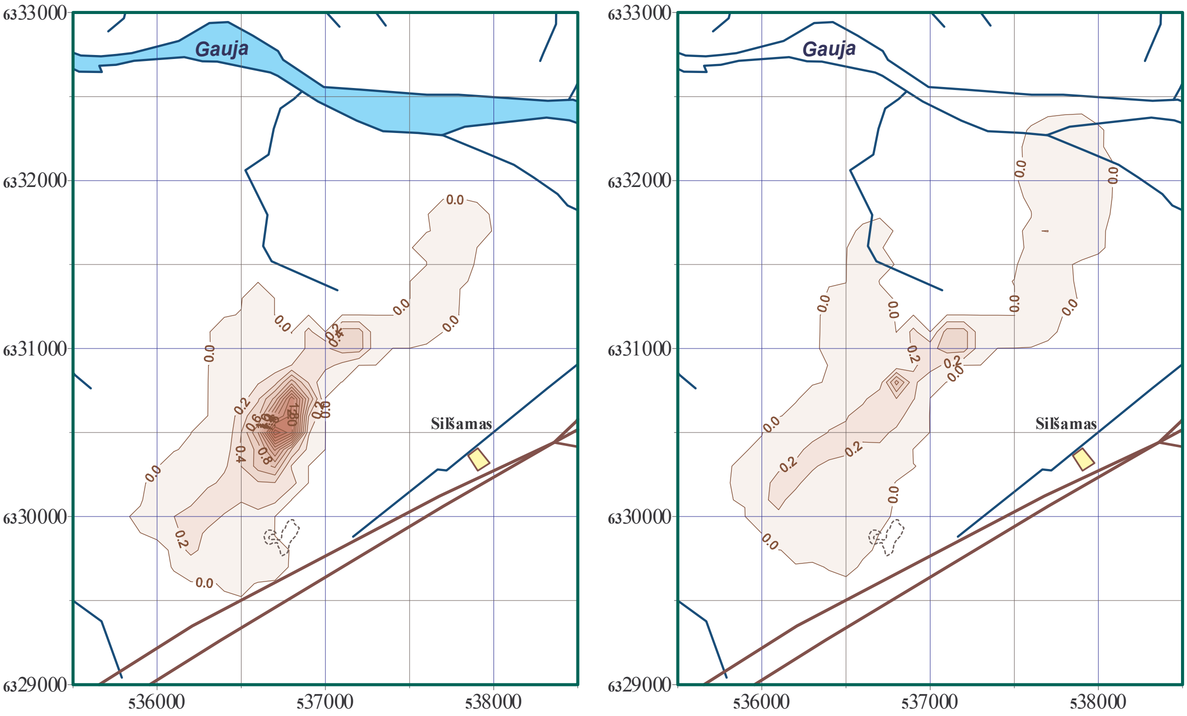


c) year 2045 D_3gj22 d) year 2045 D_3gj23

Fig. 4. Distributions of SO_4 concentrations [g / l] in 2045 for the D_3gj2 subaquifers of the Northern pool plume. The Northern pool is not excavated



a) year 2005 b) year 2015



c) year 2025 d) year 2035

Fig. 5. Distributions of SO_4 concentrations [g / l] for the Northern pool plume versus time for the **$D_3 gj23$** subaquifer if the plume is under remediation (water withdrawal 3000 m^3/day, reinfiltration of cleaned water).The Northern pool has been excavated in 2005

It follows from the above data that the Northern pool SAC plume presents the main danger for the Gauja river that runs nearby the well fields Remergi and Baltezers providing drinking water for the Riga city. Both contaminant plumes have large expanding bodies that are causing serious problems not only for the river, but also for inhabitants of the Incukalns area.

4 INVESTIGATION OF SANITATION METHODS

Firstly, the worst case (no sanitation) was considered, when the Northern and Southern pool plumes would reach the Gauja river approximately after 25 and 65 years, respectively. Each plume will enter the river into ~ 500 m wide zone where the groundwater flow is ~1000 m^3/day. For these zones, the computed mean SO_4 and SAC concentrations are, correspondingly, 500 mg/l; 2 mg/l and 300 mg/l; 0.15 mg/l, for the Northern and Southern pool plumes. These values are lower than the initial ones (year 2005) due to contaminant dilution by fresh water and also due to destruction of SAC ($t_{0.5}$ = 15 years). However, quality of groundwater there is far from the one obligatory for drinking water, especially, for the SAC fraction (2 mg/l » 0.02 mg/l).

The effect of dilution on the practically steady SO_4 concentration distribution (year 2045), for the subaquifers *D3gj21*, *D3gj22*, *D3gj23*, are shown in Fig. 4. For the two upper subaquifers, especially, for the *D3gj21* one, concentrations have strongly descreased, in comparison with the initial ones (year 2005). Such a considerable change is due to a flow of fresh water entering the *D3gj2* aquifer from above through the *gQ* aquitard. Therefore, the improved model has provided the 3D image of the SO_4 concentrations accounting for dilution processes.

To stop migration of contaminants, polluted groundwater should be pumped out and to be cleaned by a overground equipment and reinfiltrated back into the *D3gj2* aquifer. For the current stage of investigation, only rough parameters of this approach were sought and the following results were obtained:

- at least, two discharge wells should be used with the total pumping rate ~ 3000 m^3/day = 1500 m^3/day × 2; the wells should be situated in front areas of the plumes where contaminant concentrations are high enough;
- at least, three wells for reinfiltration of cleaned water (~ 3000 m^3/day) should be located before the river; the distance between the discharge and recharge lines should be 500 - 700 m.

For the both pools, such a system stops and remediates their contaminant plumes. To make modelling simpler, it was assumed that cleaned water contains no contaminants.

In Fig. 5, the disposition of discharge and recharge wells is shown for the Northern pool plume. In the area of the plume, the mean hydraulic gradient has increased 1.5 times and this factor accelerates remediation of the plume. During the first three years, the following mean SO_4 and SAC recovery rates are expected, accordingly, 1700 kg/day; 40 kg/day and 5200 kg/day; 30 kg/day, for the Northern and Southern pool plumes.

If the disposition and pumping rates of the remediation system remain fixed then recovery for contaminants should decrease versus time. To restore the rates, the system of wells should be moved upgradient to areas with higher contaminant concentrations.

The factor of reducing the contaminant outflow from the pools by blocking their interpolation flow is 1.3 and 1000 times for the Northern and Southern pools, correspondingly. The waste body of the Northern pool is located into the Q1 aquifer, and for this reason, blocking of infiltration (~ 100 mm/year) has small effect on the waste dissolution rate there. The Southern pool lays into the aeration zone, and there only the infiltration flow (~ 400 mm/year) dissolutes the waste. Thefore blocking of this flow, practically stops dissolution processes.

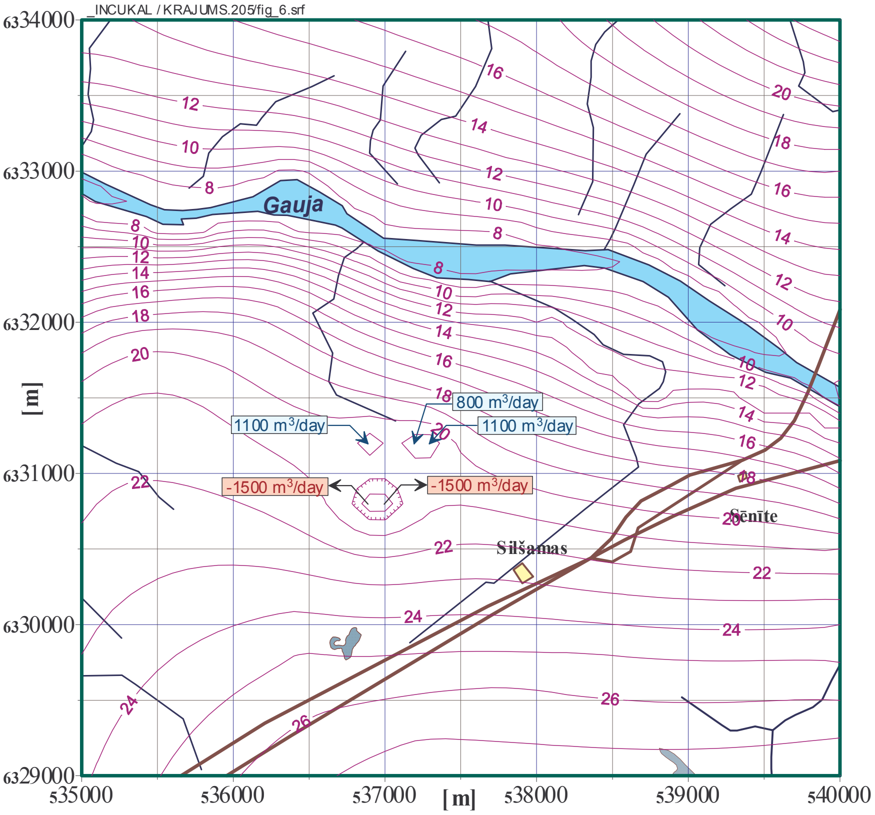


Fig. 6. Distribution of piezometric levels [m asl] for the $D_3 gj2$ aquifer it the Northern pool plume is being remediated (water withdrawal 3000 m^3/day, reinfiltration of cleaned water)

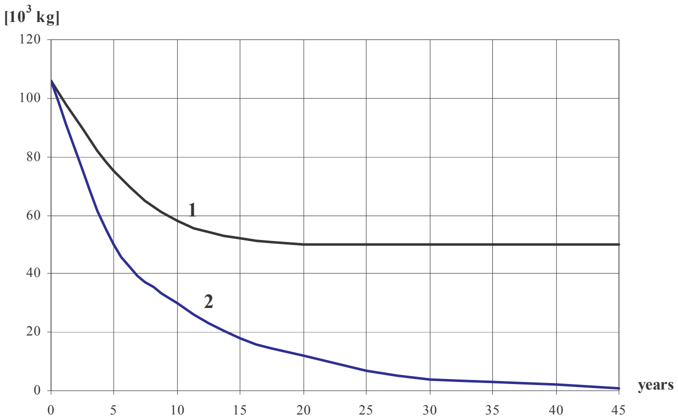


Fig. 7. The SAC mass [kg] versus time in the D3gj2 aquifer for the Northern pool plume being under remediation (water withdrawal 3000m3/day, reinfailtration of cleaned water). The Northern pool is not (graph 1) and is (graph 2) excavated in 2005.

Excavation of the waste pools may give mainly a long term effect (~ after 25 years) if no remediation of their contamination plumes is done. If the described above system containing discharge and recharge wells are used for remediation then excavation of pools may considerably improve the sanitation process, especially, for the SAC fraction.

In Fig. 6, a sequence of the SO_4 concentration images for the *D3gj23* subaquifer is given if the Northern pool has been excavated (year 2005) and its plume is being remediated (scheme of Fig. 5). Due to excavation, the SO_4 plume has practically disappeared after 30 years! For the SAC fraction, the positive effect of excavation is even more impressive. In Fig. 7, the graphs of the mass change versus time for the Northern pool plume being remediated are given if the pool is not and is excavated. If the pool is not excavated then the total SAC mass decreases twice after 15 years and then remains unchanged (1 graph). The SAC mass drops very fast if the Northern pool has been excavated (2 graph).

Summary of the main parameters accounting for remediation of the Incukalns place is given by Table 2.

Table 2

Contamination parameters accounting for remediation of the Incukalns place

Nr.	Parameters	Northern pool	Southern pool
1.	mean SO_4 concentration for first inflow into river (no sanitation) [mg/l]	500	300
2.	mean SAC concentration for first inflow into river (no sanitation) [mg/l]	2.0	0.15
3.	pumping – infiltration rate stopping contaminant migration [m^3/day]	3000	3000
4.	mean SO_4 recovery rate during first three years [kg/day]	1700	5200
5.	mean SAC recovery rate during first three years [kg/day]	40	30
6.	reduction of contaminant outflow from pool if its infiltration flow is blocked [times]	1.3	1000

5 RESULTS AND RECOMMENDATIONS

The hydrogeological model of the contaminated Incukalns place has been considerably improved and by applying it the following results have been obtained:

- the current parameters (year 2005) for the SO_4 and surface active components of contamination plumes have been obtained (Table 1);
- the worst case (no sanitation) considered;
- rough parameters of remediation methods were obtained (Table 2);

These results are preliminarily because more field data and some economic analysis are needed to use remediation schemes considered. However, the model may serve as a powerful tool helping to answer many difficult questions arising during of sanitation for the Incukalns place.

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Spalviņš A., Šlangens J., Janbickis R., Lāce I., Šķibelis V., Eglīte I., Mačāns A. Uzlabotais hidroģeoloģiskais modelis Inčukalna (Latvijā) sērskābā gudrona dīķu izraisītā piesārņojuma migrācijas novērtēšanai pazemes ūdens plūsmā.

1998. gadā tika izveidots hidroģeoloģiskais modelis piesārņotajai Inčukalna apkārtnei. Ar tā palīdzību tika iegūtas aptuvenas prognozes par SO_4 *un virsmas aktīvo vielu migrāciju pazemes ūdenī. No 2004. gada līdz 2005. gadam. Šis modelis tika būtiski uzlabots, lai ar to atrastu labākās metodes piesārņojuma areālu kustības apturēšanai un to ietekmes uz apkārtējo vidi samazināšanai. Tiek dots uzlabotā modeļa un ar to iegūto jauno rezultātu apraksts.*

Spalvins A., Slangens J., Janbickis R., Lace I., Skibelis V., Eglite, I., Macans, A. Improved hydrogeological model for evaluating contaminant migration in groundwater polluted by sulphur – sludge pools at Incukalns, Latvia.

In 1998, a hydrogeological model for the contaminated Incukalns place has been created and rough prognoses of SO_4 *and surface active components migration in groundwater have been obtained. In 2004-2005, this model has been considerably improved in order to find the best methods of stopping pollution plumes and of lessening their impact on local environment. The improved model is described and new results obtained are presented.*

Спалвиньш А., Шланген Я., Янбицкий Р., Лаце И., Шкибелис В., Элите И., Мачанс А. Улучшенная гидрогеологическая модель для оценки миграции загрязнений, которые порождены свалками сернистого гудрона Инчуклнса, Латвия.

В 1998 г. была построена гидрогеологическая модель для загрязненной территории Инчукалнса. С помощю этой модели были получены приблизительные прогнозы о миграции в подземной воде $\boldsymbol{SO_4}$ *и поверхностно активных веществ. В период 2004 г. – 2005 г. эта модель была существенно улучшена с целью поиска лучших методов остановки движения ареалов загрязнения и уменьшения их влияния на окружающую среду. Дается описание улучшенной модели и полученных новых результатов.*