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GROUNDWATER FLOW MODEL OF OIL SHALE MINING AREA

H. LIND[*]

Mining Department of Tallinn University of Technology
Ehitajate tee 5, 19086 Tallinn, Estonia

During the next decade changes are expected in the western area of the active part of the Estonia oil shale deposit since Ojamaa mine started to dewater the oil shale layer and environmental impact assessment is in the process of estimating the influence of dewatering on the site of Uus-Kiviõli mine. Aidu open cast is planned to close down in 2013 as the resources of oil shale indicated in the mine permission are ending. Closing of Viru mine in 2015 has been discussed. As the oil shale resources at Aidu and Viru area end, the mine sites will be closed and flooded. Therefore the groundwater table will increase in closed sites and will decrease in prospective areas. To estimate and visualise the situation, computational modeling of groundwater flow has been applied in most cases to estimate the future situation. The current analysis describes the process of groundwater modelling as well as offers possibilities of estimating the accuracy of the model and of the model calibration process. Water inflow rate into Estonia mine has been analysed.

Introduction

Dynamic groundwater modeling of a mining area is made because mining activity changes the total groundwater regime [1, 2]. As for the world practice, environmental problems and impacts are the same as in Estonia concerning problems with reducing groundwater table and estimating sources of water inflow into working mines [1, 3–5]. Changes in groundwater chemistry, concentrations and pathways of trace elements (contaminant flow) have often been simulated on the world scale [2, 6]. In Estonia, Erg has analysed changes in sulphate content [7], and her data can be used for dynamic modeling. For the new prospective mining areas modeling is used as a prior analysis of the impacts of mine dewatering [2, 8]. Problems, solutions, and uncertainties concerning mine site groundwater modeling are often discussed in international publications [9–12] while in Estonia this issue has been discussed briefly.

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[*] Corresponding author: e-mail *helena.lind@mail.ee*

Methodology of computational groundwater modeling

ModFlow is designed to simulate groundwater flow in steady state or in transient conditions using the finite difference method (FDM) [13, 14]. The modeled domain is divided into a grid of rectangular blocks or cells. External boundary conditions of the model grid is by default assumed to be a no-flow or impermeable boundary. The steady state flow uses the data from the first stress period of each boundary condition defined in a project. Stress period is the time span divided into time steps to gather the head values of a certain time period and pumping well intervals. For the transient flow, software prepares the data set of different periods defined for each pumping well and boundary condition for the stress periods to simulate the water flow. In other words, the observed head values or time intervals of boundary conditions or pumping well schedule are divided by software into uniform time steps.

Equation of transient ground-water flow for three-dimensional modeling is

$$\frac{d}{dx}\left(Kxx\frac{dh}{dx}\right)+\frac{d}{dy}\left(Kyy\frac{dh}{dy}\right)+\frac{d}{dz}\left(Kzz\frac{dh}{dz}\right)+W=Ss\frac{dh}{dt}, \qquad (1)$$

where Kxx, Kyy, and Kzz are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity, m/d; h is the potentiometric head, m; W is a volumetric flux per unit volume representing sources and/or sinks of water, with $W<0.0$ for flow out of the ground-water system, and $W>0.0$ for flow in, 1/d; Ss is the specific storage of the porous material, 1/m; and t is time, d.

Equation (1), when combined with boundary and initial conditions (recharge, evapotranspiration, model properties, etc), describes transient three-dimensional ground-water flow in a heterogeneous and anisotropic medium, provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions. Equation (1) solves the groundwater flow process using the finite-difference method in which the groundwater flow system is divided into a grid of cells. For each cell, there is a single point, called node, at which head value of the groundwater table is calculated.

For steady state, the storage term in the ground-water flow Eq. (1) is set to zero. This is the only part of the flow equation that depends on length of time, so the stress-period length does not affect the calculated heads in a steady-state simulation.

Groundwater modeling process

Groundwater modeling includes the following main steps – 1) study of the area and its hydrogeology, 2) collection and processing of the available data, 3) data entry into the software, 4) model execution 5) calibration and analysis of modeling results. Steps of the groundwater modeling process are shown in Fig. 1.

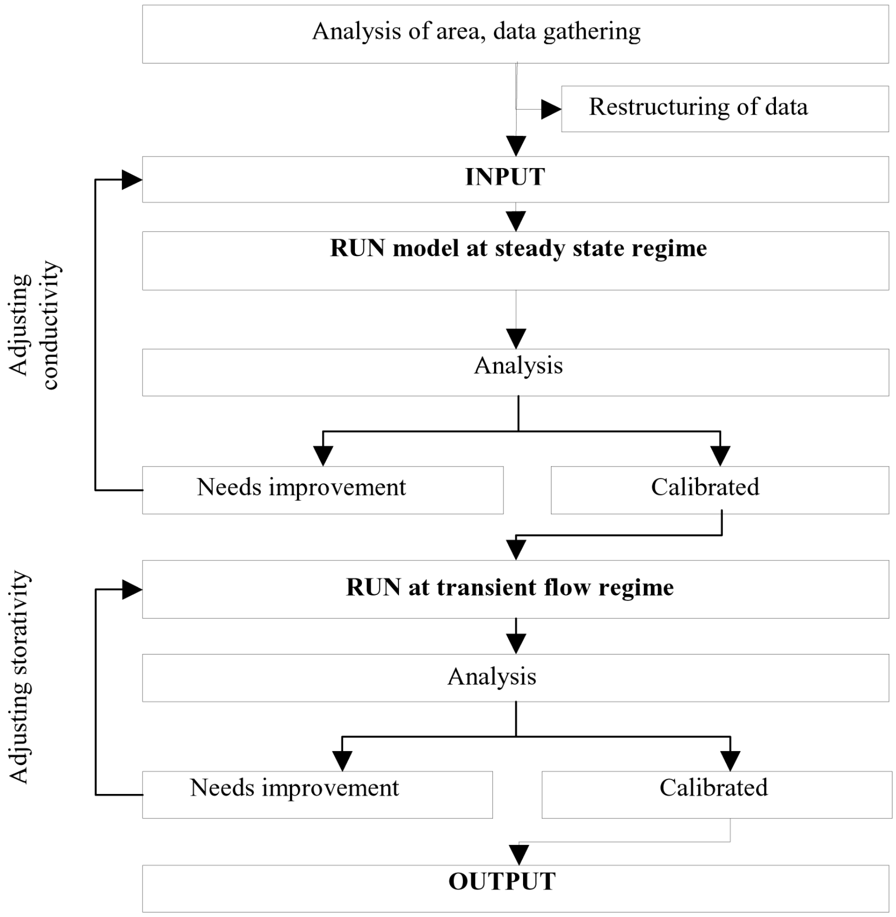

Fig. 1. Groundwater modeling procedures.

Analysed area and used data

The analysed model area includes 1650 km^2 of the oil shale deposit in North-East Estonia with 330 km^2 of mined-out land (Fig. 2). There are nine closed and water-filled underground mines in the northern and middle parts of the area and five active mine sites – Viru and Estonia underground mines and Aidu with two smaller open casts Vanaküla and Põhja-Kiviõli. The study of hydrogeological conditions was completed during collection of available information and review of previous analyses [15–18]. Field data of water table observations and mine dewatering systems during the study were gathered at Estonia underground mine and Aidu open cast. The picture in Fig. 3 depicts the pumping station of Aidu open cast.

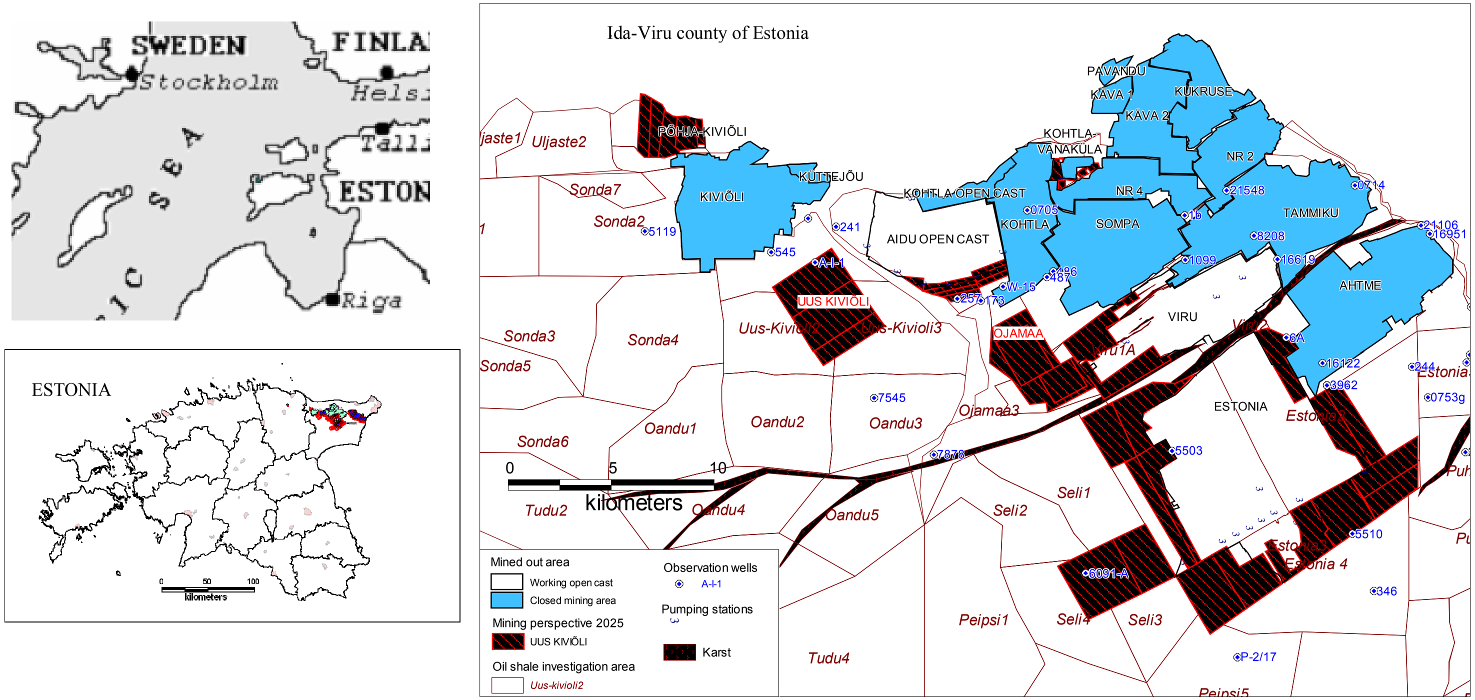

Fig. 2. Location of the investigated area.

Fig. 3. Pumping station of Aidu open cast, area observation and field measurements (picture taken by Mining department of Tallinn University of Technology).

Model dimensions

The area of the model is 42.5 km × 38 km = 1650 km^2. The model (200×200 m) is divided into grid cells but during the modeling 100×100 m grid cells of the underground mining area were used. Cell thickness is formulated by model layers. The period analysed lasted from January 2008 to December 2009 and was chosen considering the latest mine closure – Ahtme underground mine in 2002 – where the groundwater table increased and stabilised by the end of the year 2004 [1]. It is important to mention as software has difficulties in increasing the initially dry model cells and that may lead to uncertainties at the beginning of the analysed period. Time step of the model is described with monthly (30 days a step) changes by the average values of rate of recharge, and monthly pumping capacities are included into the model.

Input parameters

To build a groundwater model the requirements for the input data are large. Collecting and restructuring of the information needed is a time-intensive work and a comfortable database to generate output in the structured form is also needed. The information gathered from previous analyses and field work was assembled into comfortable data files to be used in the following step to insert into the modeling software. Data about geological layers, hydraulic conductivity, observation wells, pumping wells and boundary conditions were collected.

There were used four model layers with variable hydraulic properties describing the main geological formulations – the Quaternary layer and the oil shale top and bottom elevations were retrieved from digital well hole data, ground layer elevation was digitised from the Base Map of Estonia, and data points from digital well holes. The fourth layer corresponds to the bottom of the model, its conductivity parameters are low and it acts as an impermeable layer [14]. The overview of used input parameters and sources is given in Table 1.

The model includes 28 **observation wells** distributed within the analysed area (Fig. 2) with the observation values measured by Estonian Energy Mining Company and Geological Survey of Estonia since January 2008. These observation wells are used as calibration points with the measured water table elevations of the Keila-Kukruse aquifer. For the monitored water level data the MS Access database linked with MapInfo professional map was created [22]. Database is used to record continuously monitored observation well data in a structured form. Query tables are used to extract only the needed information from the main table as it is useful if the start time of the model changes. The query table is built so that when the start time is

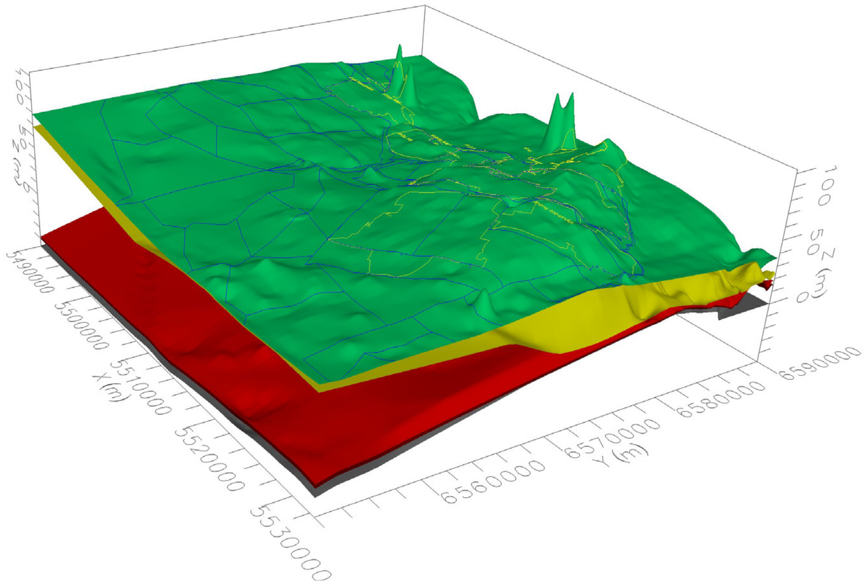

Fig. 4. Used model layers – 1) top ground surface, 2) Quaternary bottom, 3) oil shale bed top and 4) bottom, 5) aquitard layer. From the top ground the terriconics of mine tailing are visualised.

Table 1. **Overview of used data sources: MD – Mining Department of Tallinn University of Technology, BE – Digital Basemap of Estonia, EEM – Estonian Energy Mining Company, GSE – Geological Survey of Estonia, EMHI – Estonian Meteorological and Hydrological Institute, REE – Registry of Estonian Environment**

Input parameters		Source
Grid and lines	Map of mine plan	MD [19]
	Contour lines of oil shale investigation areas	EEM
	Contour lines of rivers and lakes	BE
	Oil shale outcrop area	GSE, MD [20]
	Ground and layer elevations, well hole data	MD and BE [19, 20]
Wells	Observation wells	EEM, REE, Created MS Access database
	Mine dewatering pumping wells	EEM, EEM
Properties	Conductivity	GSE, previous studies, literature [15–18]
	Initial head of water table	MD, EEM
	Storage (Specific storage, specific yield effective porosity, total porosity)	EEM, EGS, literature [15, 16, 21]
Boundaries	Recharge	EMHI, GSE, MD

changed the time steps are calculated starting from this date. The MS Access database together with linked geographic data by MapInfo Professional software allows visualizing the location of the well on a two-dimensional map and is useful for generating a grid with initial head values for the model.

The model includes **pumping stations** at active mine sites. Data on pumping capacities and locations from Estonian Energy Mining Company was structured and added to the model. Overview of pumping capacities is given in Fig. 5 where rates of precipitations are added.

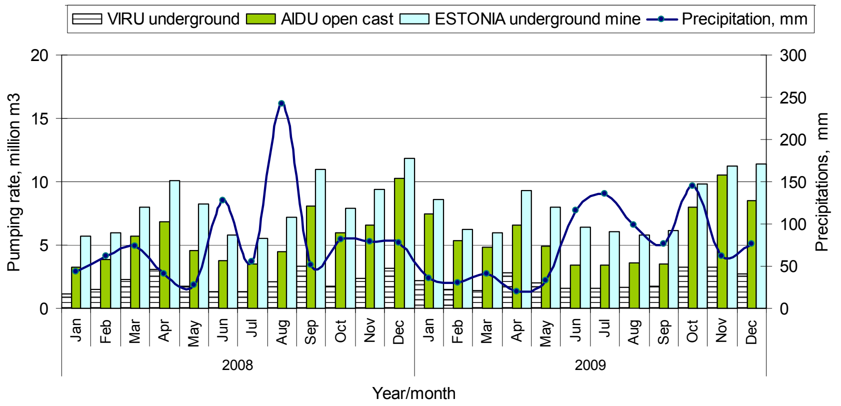

Fig. 5. Pumping capacities and rate of precipitations during the modeling period in 2008–2009.

Properties

To describe hydraulic properties for each model layer**, conductivity and storage** values were applied. The ranges of the measured hydraulic parameters of the analysed area are given in Table 2 [23, 24]. The values are indicative of ranges to vary at the calibration procedure. As the parameters vary on a large scale it may lead to uncertainties. To obtain more site-specific data, previous hydrogeological predictions and analyses by Geological Survey of Estonia were used [15, 16, 25].

Table 2. **Hydraulic property ranges of aquifer describing analysed area [23]**

Age	Aquifer system	Rock type	Depth, m	Thickness, m	Water table (piezometric), m below surface	Specific capacity, l/sec·m drawdown	Hydraulic conductivity, m/day	Transmissivity, m^2/day
Quarter-nary	Q	Sand, till, peat	0	0–77	+0.3–16	0.001–54	0.02–175	0.1–1980
Ordovi-cian	Nabala-Rakvere $\mathrm{O}_{2\mathrm{nb\text{-}rk}}$	Lime-stone, marl, dolo-stone	2–20	0–50	+0.1–13.2	0.025–11.0	0.40–185	4–2546
	Keila-Kukruse $\mathrm{O}_{2\mathrm{kl\text{-}kk}}$		0.5–50	0–44	0.2–28.2	0.007–8.3	0.04–170	0.03–2308
	Lasna-mäe-Kunda $\mathrm{O}_{2\mathrm{ls\text{-}kn}}$		0.5–100	17–24	0.6–15.6	0.001–2.1	0–48	0.01–187

There are four main zones for which the conductivity and storage values were applied – northern, southern and geological disturbances like karst and mined-out land (Table 3). Storage parameters include total porosity (P_t), effective porosity (P_{ef}), **specific yield (S_y) and specific storage (S_s).** Parameters of total and effective porosity are not directly used in groundwater flow simulation, but they are defined to be used for particle movement and to determine coefficients of chemical reactions [14]. The use of S_s or S_y in calculations depends on whether the layer is confined or unconfined. For the model, the layer is confined if the value of water table head is below the upper layer or, in other words, when the upper layer is a dry cell and water

Table 3. **Used ranges of hydraulic properties in the model**

Model zone	Geological unit	Model layer	*K*, m/d	*Sy*	*Ss*, 1/m
North	Quaternary	L1	0.1–3.6	0.32	0.068
	Limestone	L2	3–50	0.4	0.1–0.012
	Oil shale	L4	2–10	0.09	0.035
South	Quaternary	L1	0.1–3.6	0.32	0.068
	Limestone	L2	2–9	0.1	0.1
	Oil shale	L4	2–10	0.05	0.019
Mined-out area	Quaternary	L1	30–70	0.4	0.053
	Limestone	L2	15	0.4	0.004
	Oil shale	L4	999	1	0
Karst	Quaternary	L1	0.1–3.6	0.32	0.1–0.068
	Limestone	L2	*Kx*, *Ky* = 50, *Kz* = 500	0.36	0.022
	Oil shale	L4			
Source			[15, 16]	[16, 21]	calculated

table does not occur. Therefore S_y is used for unconfined and S_s for confined layer areas. For the current analysis data for the specific yield values as supported by the software developers were used [1, 14, 21]. The values of specific yield and specific storage are parameters needed to calculate storage coefficient.

Quaternary layer has the average thickness of 4.7 m and is assumed to consist of fine sand with specific yield ranges 0.01–0.46. Ranges for specific yield for limestone layer lie between 0…0.36, in Estonian conditions up to 0.46 [16]. The average thickness of the limestone layer is 16.9 m. Oil shale layer has average thickness 2.7 m and ranges for specific yield are <0.1, the porosity of oil shale is assumed to be less than 10%. Bottom clayey layer is defined as a no-flow or impermeable layer to reduce convergence problems. The model includes the zone of mined-out area and karst. The mined-out area is a void in oil shale layer. For the Quaternary and limestone layers the mined-out area is assumed to consist of coarse gravel to describe the overburden on an open-cast area. Geologically disturbed karst occurs in the middle of the analysed area (Fig. 2) and is defined in the model as the part of higher conductivity on vertical scale. Karst zone divides the area into northern and southern parts.

For the initial estimation of the water table and the general direction of the waterflow the data of surface of the starting head of the water table is needed. In order to generate the **initial head** layer, the MapInfo professional package and the Vertical Mapper add-on were used. Input values for the initial head were obtained from the observation well of the Keila-Kukruse aquifer and from the knowledge of mine dewatering, in case of which water table lowered down to the bottom layer of oil shale. The value of the initial head has to be very accurate to obtain effective calibration results [14]. The observation well values of the initial head were used for all data points.

A boundary condition of **recharge** was added to the model. The recharge rate is added as percentage of monthly precipitation values of the period 2008–2009. There are five zones for which different proportions were applied: Aidu and Vanaküla opencast with 63%, Kohtla, Mine No 2 and Sompa underground with 41%, Ahtme 40%, Tammiku 44% and Viru 42% [15, 16, 26].

The parameters given above were used in the model. Developers of the software have proposed to start from simple models [14]. Therefore, for example, the second limestone layer in our model is not divided into intermediate layers to obtain more specific conductivity values for deeper limestone layers as the conductivity increases with the depth of the layer elevation [27]. Therefore the conductivity values for the limestone layer are average ones.

Model run and estimation of results

After the data had been inserted into the model, it was run in the dynamic regime to calculate head values. The steady state was not used due to the problems of no convergence of model calculations. This situation may occur when model layers are very thin and cross with each other, for example, when nearby located grid cells of the same layer cannot exchange information with each other – they are lifted. One problem may also be the use of conductivities where mined-out underground void is characterized by high velocity of water flow – $K = 999$ m/d. Software developers are also of the opinion that transient model calculation can be used and steady state is not essential for beginning. In this case the model was run in the dynamic regime using Geometric Multi Grid Solver of ModFlow 2000 engine as a calculation method suitable for complex systems such as the mined out area.

After the model run has been completed, the results of calculations can be visualised. Firstly the accuracy of model calculation must be evaluated. To evaluate the model accuracy there are several statistical indicators generated by software. Mainly this is indicated by calibration residual which is calculated *vs* observed head differences. Accuracy of groundwater capacities is estimated by differences of water in- and outflow in defined zones. Water table contours and flow direction, velocity and magnitude maps are generated to compare the expected and generated situation. The calibration residual (R_i) is defined as the difference between the calculated results (X_{cal}) and the observed results (X_{obs}) at selected data points $i \rightarrow n$:

$$R_i = X_{cal} - X_{obs} . \tag{2}$$

The maximum and the minimum residuals at the selected observation points are reported by the software. These values indicate under- or overestimation of the calculations, whether the value is negative or positive. To estimate calibration accuracy, root mean square error (RMS) can also be used for the all period of the model. RMS is defined by the following equation:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} R_i^2}\ . \tag{3}$$

There is necessary to set a scope when the calibration is said to be achieved. During several test runs of the model it was noticed that the maximum difference in the calculated head value for all analysed periods +/– 1.5 m would be sufficient. If the maximum difference chosen is bigger, system accuracy decreases – calculated head values do not follow the trend of observed head values (Fig. 6).

If the calculations over- or underestimate observed head values, the input parameters should be adjusted. From the shape of the curve of the graph and statistical parameters, *R* and *RMS* are indicative. In order to adjust the flow model, Darcy's law should be taken into consideration:

$$q_x = -K_x \frac{\delta h}{\delta x}, \tag{4}$$

where

q_x – discharge into direction x,

K_x – hydraulic conductivity, m/d,

$\frac{\delta h}{\delta x}$ – rate of head changes in the direction *x* (hydraulic gradient).

If the head gradients in a model are too high, Darcy's law indicates that the modeled recharge rates are high and/or the used conductivities must be increased. In our case it was assumed that the rate of recharge is correct, and no changes were made.

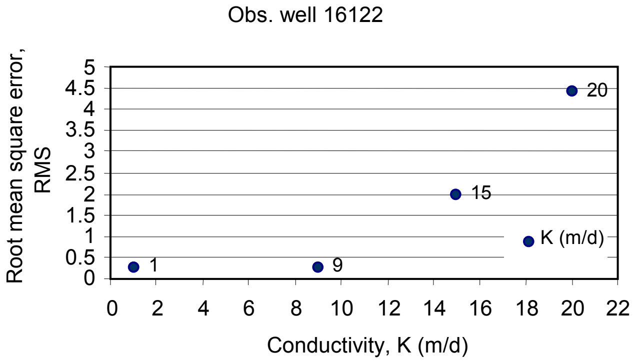

Fig. 6. Variations in conductivity affecting error of RMS.

Adjustment of the input parameters of conductivity and storage values using the data of the observation well No 16112 located in the the Ahtme mine is described below. For calibration of the process the model input parameters were adjusted. That was done changing only one parameter with time. The analysis was made using the values of conductivity and specific storage which enabled to achieve the lowest error of *RMS* and residual *R*. Figure 6 describes the variations at conductivity ranges 0.5–9 m/d. The best result with the lowest *RMS* error of 0.26 with the conductivity value of $K = 9$ m/d was achieved. The lower conductivity value did not reduce the *RMS* value.

At transient state storage parameters were used. The observation well No 16122 is located in the zone where the upper layer is dry and acts as a confining one. Therefore specific storage parameter changes were tested. During the analysis *RMS* value did not change, and therefore the maximum residual was used to describe the result of variations with S_s (Fig. 7). The smallest residual was achieved with the value $S_s = 0.1$ m^{-1}.

Adjustment of input parameters is illustrated in Fig. 8 where the observed values of groundwater table head are compared with calculated ones. Head values calculated using parameter values $K = 9$ m/d and $S_s = 0.1$ gave the lowest residual $R = -1.28$ m. While there was set a scope to have maximum residual *R* less than +/–1.5 it can be said that we have a sufficient fitting of calculated head values. Figure 9 demonstrates the comparison of the calculated head value with the observed water table elevations.

The method described here with input data of observation well No 16122 was used to adjust hydraulic properties in the model area, in the zone including all 28 observation points. The model was assumed to be accurate if *RMS* value is less than +/–1.5 m; in our case the result –0.81 m was achieved. Calculated and observed head values of the model correlate well as the correlation coefficient calculated by the software is 0.97. The coefficient close to 1 shows that both values are in good agreement. Correlation coefficient near zero would indicate minimal or no relation between calculated and observed head values.

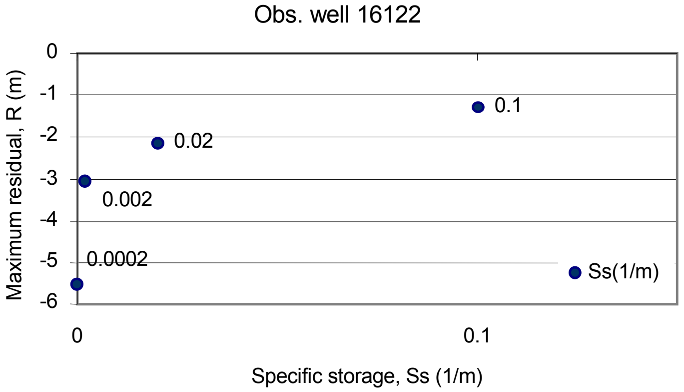

Fig. 7. Variations in specific storage affecting maximum residual R.

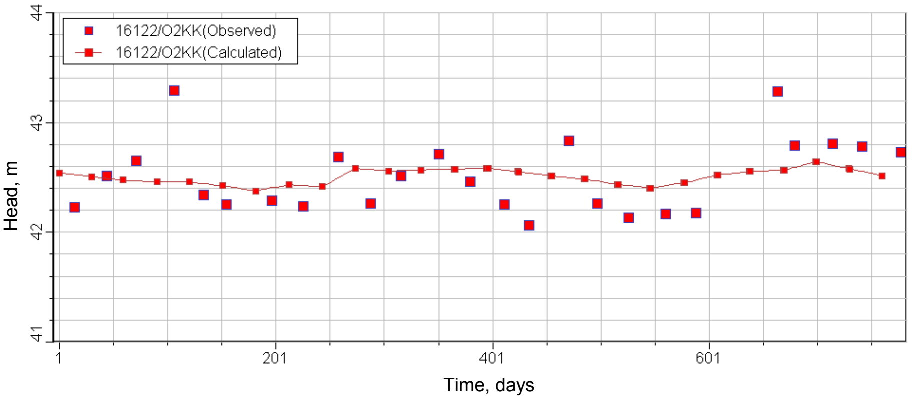

Fig. 8. Comparison of calculated and observed head values after adjustment of input parameters, RMS = 0.26, $R_{max} = -0.81$ m.

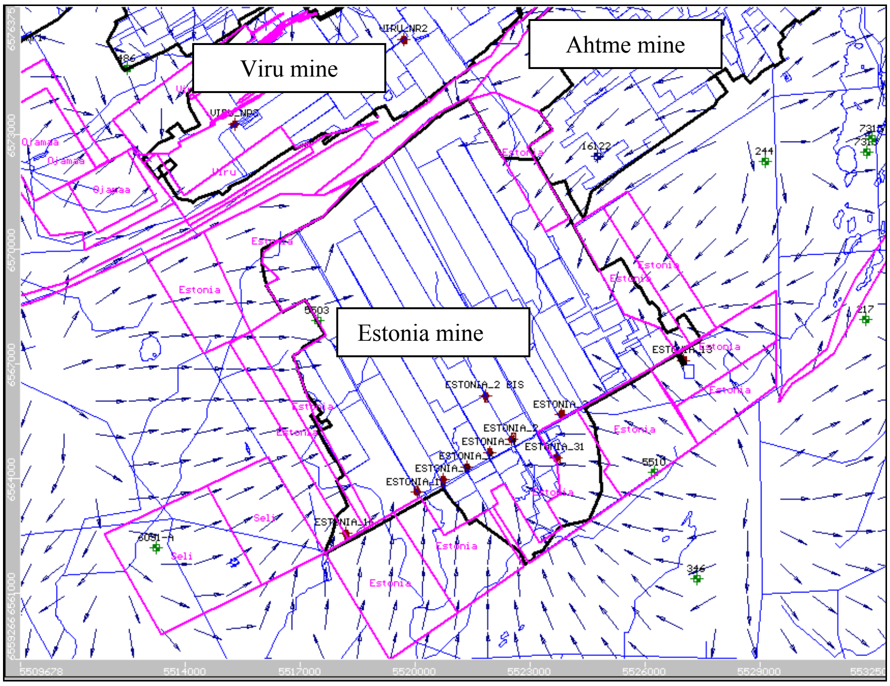

Fig. 9. Example of water inflow into working oil shale underground mine in December 2009 (model time step 760 days).

After model calibration and adjustment of input parameters the results of software calculations can be extracted. The rate of water flow from the closed Ahtme mine into the Estonia underground mine was determined as an example to compare the results with analytical calculations of the previous research [1]. To see the water flow movement, the figure provided in Fig. 9

demonstrates the direction of water flow. Well is seen the waterflow from the Ahtme side into Estonia mining area.

Estimation of the budget zones of the mines – Estonia, Ahtme-Estonia and Viru – is illustrated in Fig. 10.

In our previous work water exchange between two mines was calculated analytically, and annual water flow was found to be 6.48×10^6 m^3 with 17×10^3 m^3/day from Ahtme underground mine into Estonia mine [1]. The current analysis gave for the rate of water inflow from the Ahtme mine site 27×10^3–42.8×10^3 m^3/day. The increase of specific storage and reduction of conductivity value were also tested by separate model runs, but the differences were insignificant – 20 to 80 m^3/day less than described in the first case. The future research could enable to calculate all the water exchange rates between the mine sites with dynamic model.

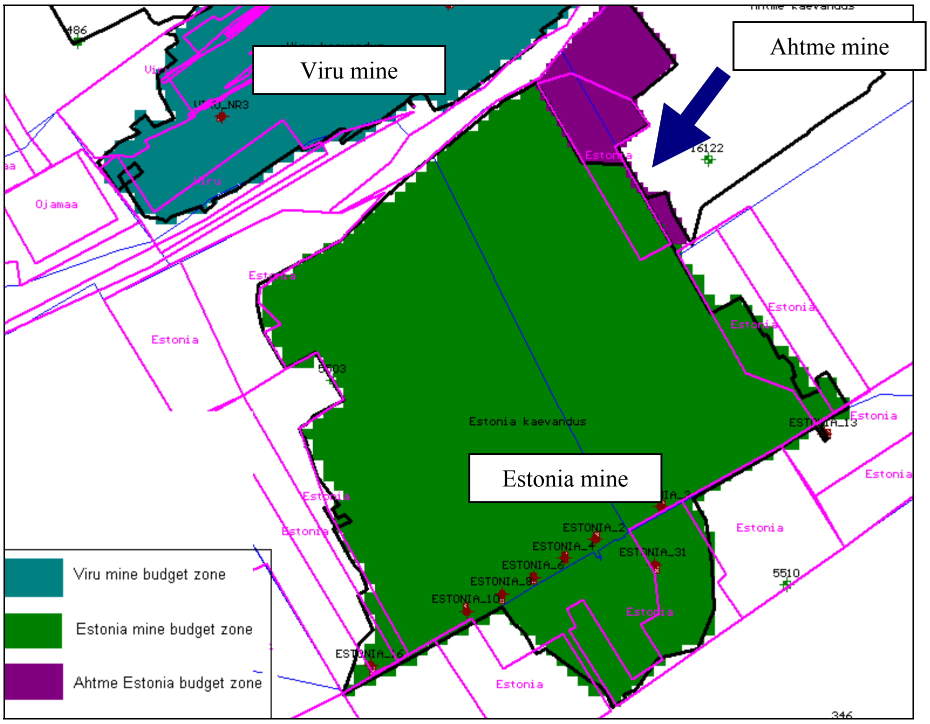

Fig. 10. Schematic picture of the defined budget zones of water in- and outflow.

Conclusions

In this research a basic model of dynamic groundwater flow was elaborated. It can be used for further estimations. The model enables to calculate the values of parameters needed for local conditions and describes how to reach the best correlation between conductivity value and sensitivity on specific storage values.

The accuracy of the groundwater flow model can generally be estimated using correlation coefficient of calculated and observed water table values for the all time period of the model run. The model described here is characterized by correlation coefficient of 0.97. To estimate locally model behaviour to the real situation the root mean square and maximum residuals can be used together with graph of calculated and observed values.

Acknowledgements

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