THESIS ON POWER ENGINEERING,
ELECTRICAL ENGINEERING, MINING ENGINEERING D44

Groundwater Flow Model of the Western Part of the Estonian Oil Shale Deposit

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Dissertation was accepted for the defence of the degree of Doctor of Philosophy in Power Engineering and Geotechnology on May 17, 2010

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Defence of the thesis: June 17, 2010

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

Helena Lind

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ISSN 1406-474X
ISBN 978-9949-23-003-7

ENERGEETIKA. ELEKTROTEHNIKA. MÄENDUS D44

Eesti põlevkivimaardla lääneala veerežiimi mudel

HELENA LIND

TTÜ KIRJASTUS

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PAPER I Reinsalu, E.; Valgma, I.; **Lind, H**.; Sokman, K. Technogenic water in closed oil shale mines. Oil Shale, 23 (1), 15 - 28. Tallinn: Estonian Academy of Publishers, 2006

PAPER II Valgma, I.; Västrik, A.; **Lind, H.** (2006). The Modelling of Oil Shale Mining Development and its Influence to the Environment. In: EU legislation as it affects mining: proceedings of TAIEX Workshop in Tallinn: INFRA 22944 TAIEX Workshop, Tallinn, 30.11.-02.12.2006. (Toim.) Valgma, I ; Buhrow, Chr.. Tallinn: Tallinna Tehnikaülikool, 2006, 126 - 130.

PAPER III Valgma, I.; **Lind, H**.; Erg, K.; Sabanov, S. The future of oil shale mining related to the mining and hydrogeological conditions in the Estonian deposit. In: 4th International Symposium "Topical problems of education in the field of electrical and power engineering". Doctoral school of energy and geotechnology. [Proceedings volume 1] : Kuressaare, Estonia, January 15-20, 2007: 4th International Symposium "Topical problems of education in the field of electrical and power engineering", Kuressaare, January 15-20, 2007. (Toim.) Lahtmets, R.. Tallinn: Tallinn Technical University, 2007, 104 - 107.

PAPER IV Erg, K.; Karu, V.; **Lind, H**.; Torn, H. Mine pool water and energy production. In: 4th International Symposium "Topical problems of education in the field of electrical and power engineering" : doctoral school of energy and geotechnology: 4th International Symposium Topical Problems of Education in the Field of Electrical and Power Engineering, Kuressaare, 15-20.01.2007. (Toim.) Lahtmets, R.. Tallinn: Tallinn University of Technology Faculty of Power Engineereing, 2007, 108 - 111.

PAPER V **Lind, H**.; Robam, K.; Valgma, I.; Sokman, K. Developing computational groundwater monitoring and management system for Estonian oil shale deposit. Agioutantis, Z.; Komnitsas, K. (Toim.). Geoenvironment & Geotechnics (Geoenv08) (137 - 140). Heliotopos Conferences, 2008

PAPER VI **Lind, H.** Computational groundwater model of west area of Estonian Oil Shale deposit as modern tool for estimations. Lahtmets, R. (Toim.). 8th International Symposium "Topical problems in the field of electrical and power engineering. Doctoral school of energy and geotechnology". II : Pärnu, Estonia, 11.01.-16.01.2010 (125 - 128). Tallinn: Elektriajam, 2010

PAPER VII **Lind, H.** Groundwater Flow Model of Oil Shale Mining Area. Manuscript accepted by Estonian Academy of Publishers, Oil Shale, 2010.

1. INTRODUCTION

At Estonian oil shale mining area groundwater regime changes occur when an old mining site is closed and water filled or when a new mine is opened (PAPER I). Today in oil shale deposit six mine sites are active– Viru and Estonia underground mines, Aidu, Vanaküla and Põhja-Kiviõli open casts; Ubja opencast is not analysed here being further from the analysed area. At the following decade there are expected changes at west area of active part of Estonian oil shale deposit while Ojamaa mine started to dewater the oil shale layer and environmental impact assessment is on process to estimate Uus-Kiviõli mine site influence. Aidu open cast is planned to close at 2013 as the resources of oil shale by the mine permission are ending. Discussion has been to close Viru mine at 2015. While the mine site is closed several problems have arisen from the flooding of the areas. First, the technogenic water body affects the amount of the water pumped out of the working mines and its seasonal variation. The water of the closed mines will influence the new mine fields, Ojamaa and Uus-Kiviõli. Secondly, the environment is affected by the water that in several places groundwater level has risen to the pre-mining level and some flooding or springs are formed. Third, the water of Estonian oil shale deposit comprises about ten closed and stopped mines that are fully or partly filled with water. As the closed underground mines are water filled consisting 3…36 mln m^3 water (PAPER I), the underground pools can be used for (PAPER IV) innovative purposes such as use of power plant cooling for example. Also there would be under interest to use 7-8 degree mine water to produce heat-pump energy for nearby district.

Beside the constraints of environmental aspects due to decreasing groundwater level, the mine dewatering is expensive part of oil shale production - pumping capacities are very large, depending on seasons 10 up to 40 m^3 per produced oil shale tonnage (PAPER V, PAPER VI). For the usage of natural resources mining company has to pay taxes. At year 2009 “Eesti Energia Mining” removed 260 mln m^3 of groundwater. On usage of ground- and drinking water at year 2009 Eesti Energia Mining paid approximately 90 mln kr taxes (PAPER VII). As the taxes have increasing trend and environmental protection has important role for mining permissions, there might be economically feasible to apply modern technology to avoid groundwater inflow into mine site to reduce pumping costs and expenditures on taxes, avoid impact on social welfare and environment. Nowadays computer assisted groundwater modelling is used for the study of groundwater flow and visaualise the situation. Flow models are built to simulate a particular groundwater system in order to predict how this system behaves in the future for an expected disturbance of the groundwater regime. More often the groundwater flow models are used to simulate and predict mining activity influences.

Current research has three main objectives:

- describe possibilities of estimation dynamic groundwater modelling system accuracy and procedure of reducing uncertainties;

- analyse criteria for choosing best available groundwater and dewatering prediction system for Estonian oil shale deposit.

For achieving these goals following methods will be applied:
- build dynamic base model of groundwater flow of the Estonian oil shale mining conditions for further investigations;
- influence on the result of calculated groundwater table values by varying the hydraulic properties of input parameters;
- visualise the use of impermeable wall and it’s possibilities to exceed the constraints concerned with the environmental questions and groundwater inflow into mine site.

2. GROUNDWATER MODELLING

Geology in nature can be anisotropic and heterogenic as it is at oil shale deposit where descriptive properties of aquifer as conductivity, porosity and storage vary by location. Computer assisted mathematical modelling is used to consider all these variations spatially for simulations of groundwater flow, solute or particle transport pathways movements. Flow models are built to understand groundwater system bearing at particular observed manner and to predict how a flow behaves in future while certain disturbances of groundwater regime are expected [1][2]. Groundwater flow model can be used for simulating water table change in time and different situations, for pumping rate optimisation. Transport model assumes firstly calibrated groundwater flow model [2]. Current analyse used Visual ModFlow Professional 4.2 software.

2.1 World practice of modelling at the mining area

Dynamic groundwater modelling of mining area is used as the mining activity changes groundwater regime (PAPER I) [3]. At the world practice problems and impacts have similar issues as in Estonia concerning problems with reducing groundwater table and estimating sources of water inflow into working mine [1][4][5][6]. More often groundwater chemical changes, concentrations and trace element pathways (contaminant flow) are simulated at world scale [3][7]. In Estonia there are made analyses of sulphate content change by Erg, K 2005 [8] which data could be used for dynamic modeling. For the new mining prospect areas the computational simulations are used as prior analyse of the impacts of mine dewatering [3] [9]. Problems and solutions, uncertainties concerned of mine site groundwater modelling are more often discussed at the international publications [1][10][11][12] while at Estonia briefly this issue is discussed.

In Estonia groundwater modelling is also used for predictions of mine development and groundwater table changes. Used software in Estonia is mostly Visual ModFlow Professional and Groundwater Modelling System by Geological Survey of Estonia. By L. Vallner at Tallinn University of Technology Geology Institute there is created model of territory of Estonia with surrounding Baltic Sea and Lake Peipsi including the territory of Estonia with area of *ca* 88 000 km^2[13]. By L. Savitski and V. Savva created groundwater models at Geological Survey of Estonia [14][15] are aimed for hydrogeological predictions of the mining environmental impact due to groundwater changes of oil shale mining activities. There are created local static models using scenario cases where the water table is dewatered at certain level - below mineable oil shale layer at mining area. Results of described models are very useful to understand the concepts and situation of the ground water flow in general.

Current analyse is a new approach where model calculations at dynamic regime are developed - rate of recharge, pumping stations are used as engines to start the water flow [16]. Using pumping wells to dewater mining area to simulate groundwater table changes is new approach at Estonian scale. At Estonia barrier pillars, infiltration dam or impermeable walls are not very often used. There is created infiltration dam at Narva surface mine to reduce mining dewatering influence [17] which influence was evaluated by modeling by private company AS Maves [18].

2.2 Methodology of computational groundwater modelling

ModFlow is designed to simulate groundwater flow at steady state or transient conditions using finite difference method (FDM) [2]. The steady state flow uses the data from the first stress period of each boundary condition defined in your project. Stress period is the time span divided into time steps to gather the certain time period head values and pumping well intervals. For the transient flow software prepares the data set of different time period defined for each pumping well and boundary condition into the stress periods to simulate the water flow. 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 modelling is

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

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. The groundwater flow process solves equation 1 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 a node, at which head value of groundwater table is calculated.

For steady state, the storage term in the ground-water flow equation (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.

2.3 Groundwater modeling process

Groundwater modelling 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 modelling results. Process steps of groundwater modelling are given at the Fig. 1.

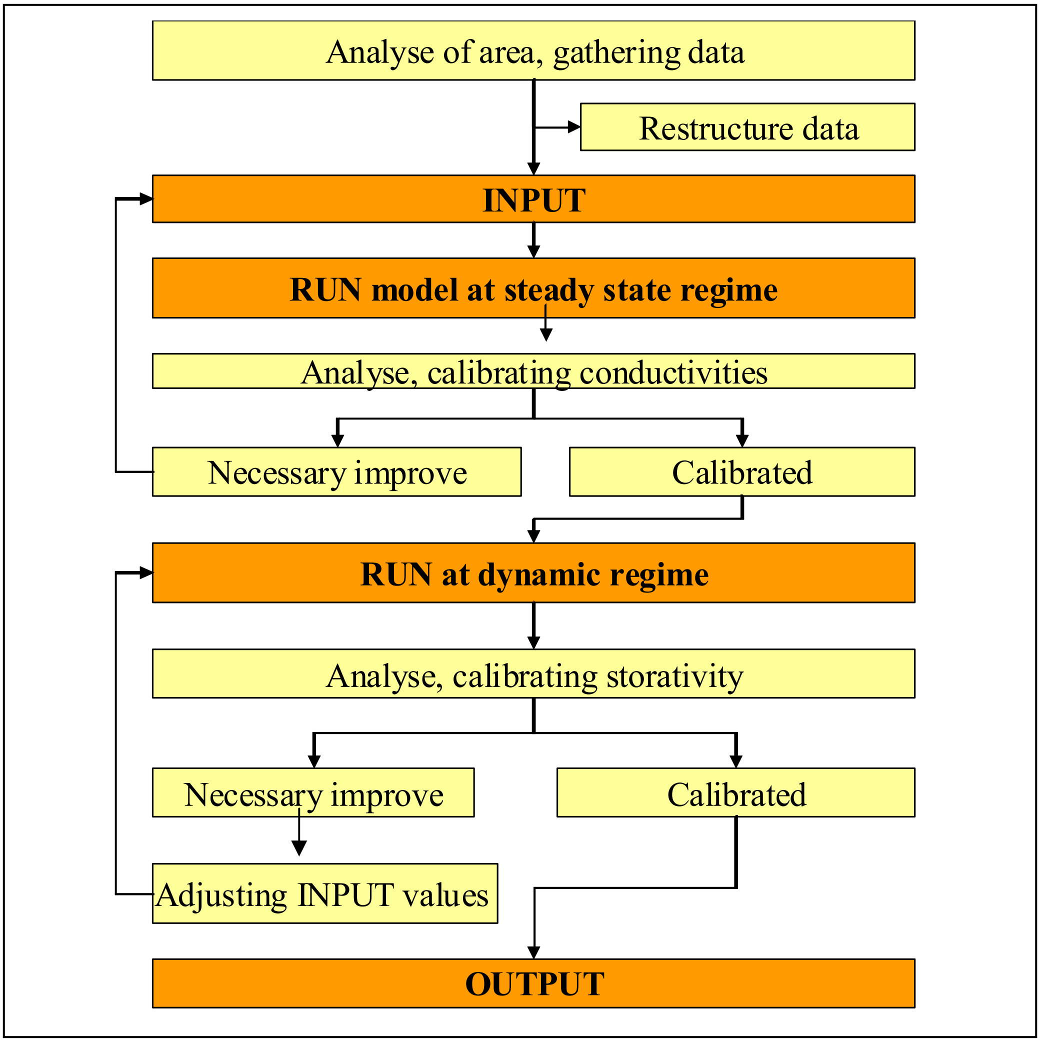

Fig. 1 Groundwater modelling procedures.

3. GROUNDWATER MODEL OF OIL SHALE DEPOSIT

3.1 Analysed area and used data

Analysed model area includes 1650 km^2 of oil shale deposit at north east of Estonia within 330 km^2 of mined out land (Fig. 4). Area includes nine closed and water filled underground mines at northern and middle part of the area. There are five active mine sites- Viru and Estonia underground mines and Aidu with two smaller open casts Vanaküla and Põhja-Kiviõli. As previously described modeling main steps, firstly the data was collected, gathered and analysed. The study of the hydrogeological conditions was completed during the collection of the available information and the review of previous analyses (PAPER I, [14] [15] [17] [18]).

There were made field measures of water table observations and mine dewatering systems during the study – at Estonia underground mine and Aidu open cast. Picture at Fig. 2 visualises pumping station of Aidu open cast.

Fig. 2 Pumping station of Aidu open cast, area observation and field measures (Picture taken by TUT Mining department)

The following Fig. 3 describes the problematic situation of nearby located mine sites where water filled mine is next to the working open cast and is source of water inflow. This important to consider while new mine sites will be taken into use, to consider using impermeable walls or infiltration dams to reduce water inflow and costs for pumping.

Fig. 3 Water inflow into Aidu open cast from the side of Kohtla closed underground mine

3.2 Model dimensions

Area of the model is 42.5 km x 38 km =1650 km^2. Model is divided into grid cells with spacing 200x200m and during the modelling finally 2 times refined (100x100m) grid cells at underground mining area was used. Cell thickness is formulated by the model layers. Time period analysed is from January 2008 - December 2009. This is chosen considering latest mine closure of Ahtme underground mine at 2002 where the groundwater table has increased and stabilised at end of year 2004 (PAPER I). This is important to mention as software has difficulties to increase the initially dry model cells and may lead to uncertainties at the beginning of the analysed time period. Time step of the model is described with monthly (30 days a step) changes by the average values of rate of recharge and pumping capacities per month are described into model.

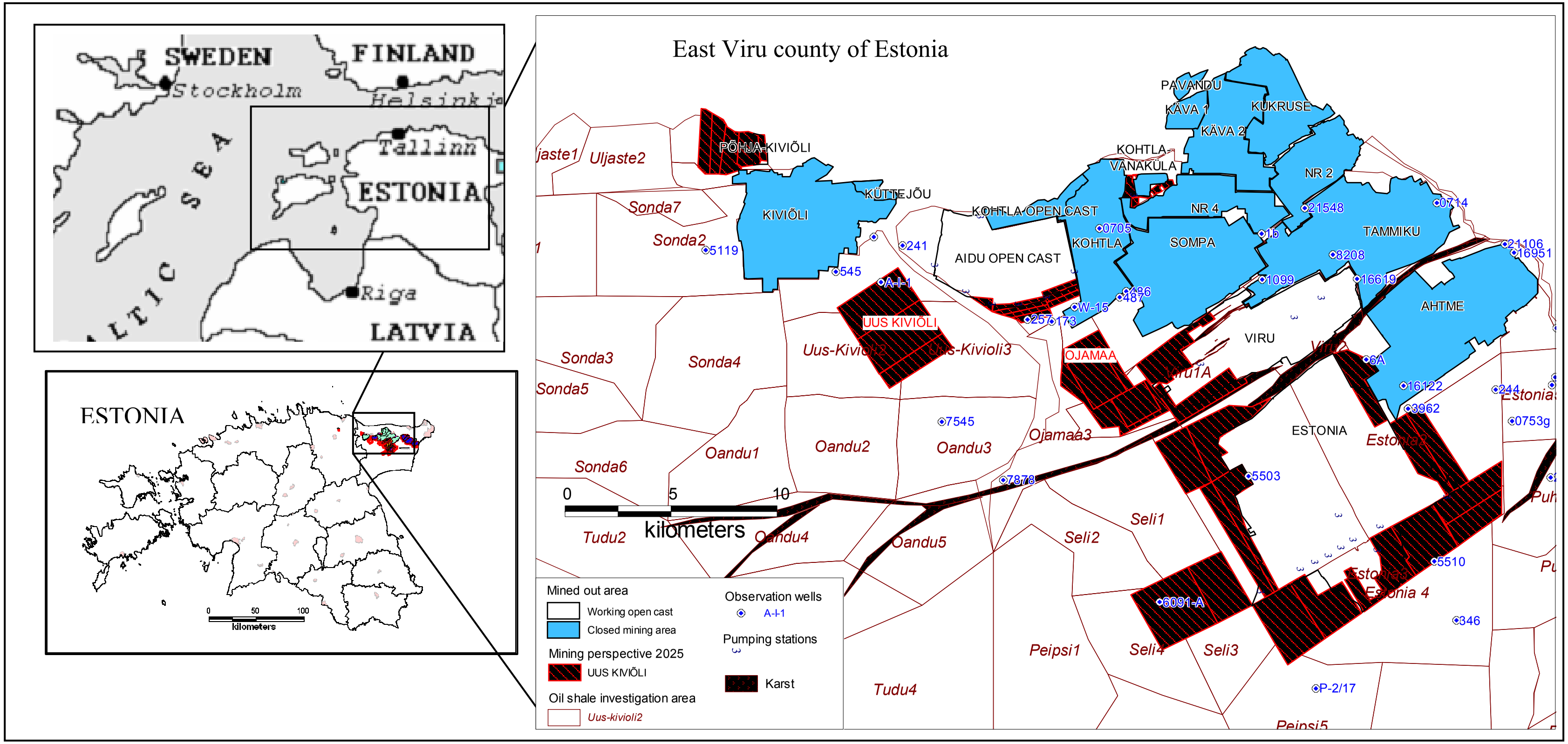

Fig. 4 Location of the analysed area

3.3 Input parameters

To build the groundwater model the input data requirements are large. Collecting and restructuring of the information needed is time intensive and there is useful comfortable database to generate output at structured form. The information gathered from the previous analyses and field work was inserted into comfortable data files for the following step to add into the modelling software. Data about geological layers, hydraulic conductivity, observation wells, pumping wells and boundary conditions where collected.

There are used four model layers with variable hydraulic properties describing the main geological formulations - the quaternary layer and the oil shale top and bottom elevations 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 and it has defined as no flow layer as it acts as impermeable layer [16]. Overview of used input parameter and sources are described at Tab. 1.

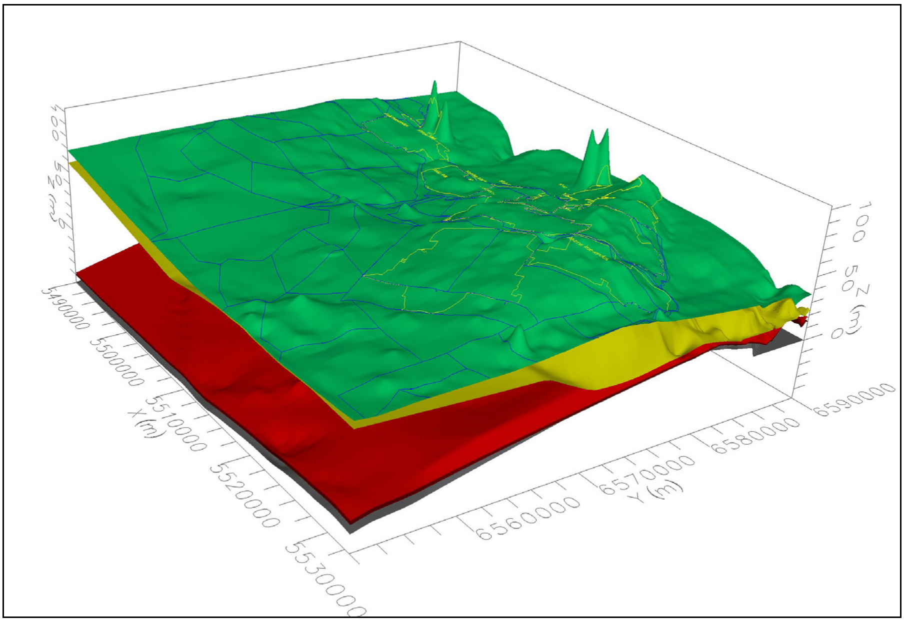

Fig. 5 Used model layers – 1)top ground surface, 2) bottom quaternary, 3) oil shale bed top and 4) bottom, 5) aquitard layer. From top ground the higher points are terriconics of mine tailing.

Tab. 1 Overview of used data sources: MD – Tallinn University of Technology Mining Department, 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 [20]
	Contour lines of oil shale investigation areas	EEM
	Contour lines of rivers and lakes	BE,
	Oil shale outcrop area	GSE, MD [22]
	Ground and layer elevations, well hole data	MD and BE, [20] [22]
Wells	Observation wells	EEM, REE, Created MS Access database
	Mine dewatering pumping wells	EEM, EEM
Properties	Conductivity	GSE, previous studies, literature. [14] [15] [17] [18]
	Initial head of water table	MD, EEM
	Storage (Specific storage, specific yield effective porosity, total porosity)	EEM, EGS, literature [14] [15][24]
Boundaries	Recharge	EMHI, GSE, MD

Model has 28 **observation wells** distributed at the analysed area (*Fig. 4*) with the observation values since January 2008 measured by Eesti Energia mining and Geological Survey of Estonia. These observation wells are used as calibration points with the measured Keila-Kukruse aquifer water table elevations. For the monitored water level data the MS Access database linked with MapInfo professional map was created (PAPER V). 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 when the start time of the model may change at different projects. The query table is built so, that when the start time is 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 well location on a two dimensional map and is useful to generate grid with initial head values for the model.

The model includes **pumping stations** at active mine sites. Data of pumping capacities and locations from “Eesti Energia mining” was structured and added into model. Overview of pumping capacities is given in Fig. 6 where rate of precipitations is added. It can be seen that a month after the higher rate of precipitations the pumping rate increased (Aug.-Sept. example)

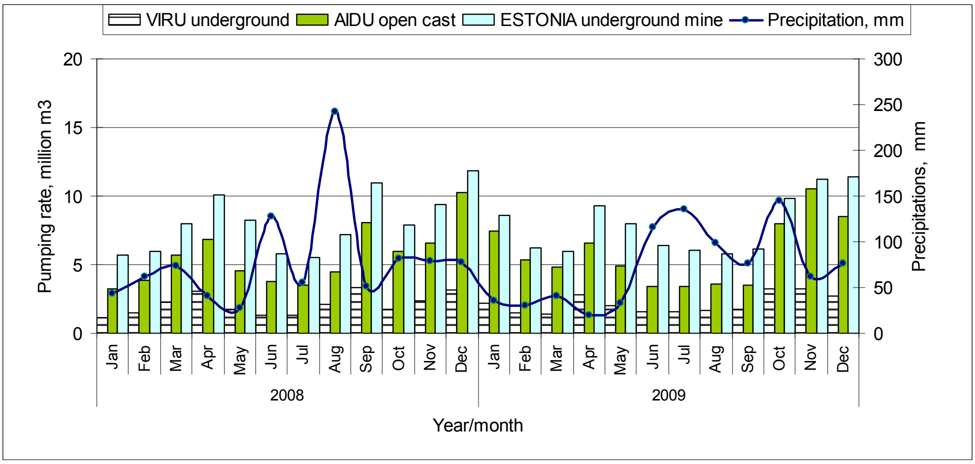

Fig. 6 Pumping capacities and rate of precipitations at the modelling time period of years 2008-2009

Totally model has 35 pumping stations locating in the working mine sites – Aidu, Vanaküla, Viru, Estonia, Ojamaa.

3.4 Properties

To describe for the model hydraulic properties for each model layer**, conductivity and storage** values are applied. The ranges of the measured hydraulic parameters of the analysed area are described at the Tab. 2 (PAPER IV) [25]. The values are indicative for ranges to vary at the calibration procedure. As the parameters vary at large scale it may lead to uncertainties. To obtain more site specified data, previous hydrogeological predictions and analyses by Geological Survey of Estonia was used (PAPER I) [14][15][26].

For the model the property zones of hydraulic parameters where defined by layer and by layer zones. There are four main zones at each layer where the conductivity and storage values were applied– northern, southern and geological disturbances like karst and mined out land. Quaternary layer has average layer thickness of 4.7 m and is assumed as fine sand with specific yield ranges 0.01…0.46. Ranges for specific yield for limestone is 0…0.36. Thickness of limestone layer is average 32.5 m while the thickness increases into south being between 0.5…96 m. Oil shale layer has average thickness 2.6 m and ranges for specific yield are <0.1 as the porosity of oil shale is assumed to be less than 10%. Bottom clayey layer is defined as no flow or impermeable layer to reduce convergence problems of model calculations. Model has zone of mined out area and karst. Mined out area is meant for oil shale layer the underground mined out area, consisting of void. For the quaternary and limestone layer the mined out area is assumed to be coarse gravel to describe the overburden at open cast area. Geologically disturbed karst occurs in the middle of analysed area (Fig. 4) and is defined into model with higher conductivity at vertical scale. Karst zone divides the area into northern and southern part (Tab. 3).

Tab. 2 Hydraulic property ranges of aquifer describes analysed area.

Age	Aquifer system	Rock type	Depth, m	Thick-ness, m	Water table (piezo-metric), m below surface	Specific capacity, l/sec/m drawdown	Hyd-raulic Con-duc-tivity, m/day	Trans-missi-vity, 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 O2nb-rk	Lime-stone, marl, dolostone	2-20	0-50	+0.1-13.2	0.025-11.0	0.40-185	4-2546
	Keila-Kukruse O2kl-kk		0.5-50	0-44	0.2-28.2	0.007-8.3	0.04-170	0.03-2308
	Lasnamäe-Kunda O2ls-kn		0.5-100	17-24	0.6-15.6	0.001-2.1	0-48	0.01-187

Storage parameters include total porosity (P_t), effective porosity (P_{ef}), **Specific yield (S_y) and specific storage (S_s).** Total and effective porosity parameters are not directly used in groundwater flow simulation, are defined to use for particle movement and to determine chemical reaction coefficient [16]. The use of S_s or S_y in the calculations depends if the layer is confined or unconfined. For the model, the layer is confined while the water table head value is below upper layer or other words when upper layer is dry cell and water table does not occur. Therefore S_y is used for unconfined and S_s for confined layer areas. Current analyse used data from literature for the specific yield values as is supported by the software developers Specific storage was estimated using ratio of average layer thickness and specific yield [1][16][24]. Specific yield or storage values are parameters to calculate storage coefficient at the software calculations.

Tab. 3 Used ranges of hydraulic properties at the model

Model zone	Geological unit	Model layer	K (m/d)	Sy (-)	Ss (1/m)
North	Quaternary	L1	0.1...3.6	0.32	0.1...0.068
	Limestone	L2	3...50	0.2	0.1...0.012
	Oil shale	L4	2...10	0.09	0.1...0.035
South	Quaternary	L1	0.1...3.6	0.32	0.1...0.068
	Limestone	L2	2...9	0.15	0.1...0.003
	Oil shale	L4	2...10	0.05	0.1...0.019
Mined out area	Quaternary	L1	30...70	0.25	0.053
	Limestone	L2	15	0.19	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			[14] [15] [26]	[24]	calculated

For the initial „estimation" of the water table and the general direction of the waterflow the 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 was used for generating **initial head**. Input values for the initial head was applied from the observation well head values of the Keila-Kukruse aquifer and from the knowledge of mine dewatering, where water table is lowered down to the bottom layer of oil shale at mining area. Initial head has to be very accurate to reach faster the effective calibration results [16]. For the initial head values observation well values were used at all available data points.

There is added a boundary condition of **recharge** into model. The recharge rate is added as percentage of monthly precipitation values at time period 2008-2009. There are following zones where different proportions are applied: Aidu and Vanaküla opencast with 63%, Kohtla, Mine No 2 and Sompa underground with 41%, Ahtme 40%, Tammiku 44% and Viru 42%. The overall area has 33% of monthly precipitations [14][15][26].

Previously described model parameters were applied into model. As it is supported by the software developers to start from simple to complex [16] the model tried to keep as simple as possible. Therefore for example the second layer of model defined as limestone is not divided into intermediate layers to obtain more specific conductivity values as the conductivity increases with the depth of the layer elevation [26]. Therefore the conductivity values can be said as average for the all limestone layer.

4. MODEL RUN AND ESTIMATION OF RESULTS

After the data is inserted into model it was run at dynamic regime to calculate head values. Steady state was not used due to problems of no convergence of the model calculations. This situation may occur when there are very thin model layers and the layers are "crossing" with each other having very small layer thickness (0.1 m) and there are steep. For example when nearby located grid cells of the same layer can not exchange information with each other and are lifted. Problem might be also the use of conductivities where mined out underground void has high velocity of water flow K=999 m/d. It is allowed to run model transient state, it is not essential for begin at static regime. Model was then run at the dynamic regime using Geometric Multi Grid Solver of ModFlow 2000 engine as suitable calculation method for complex system that the mined out area is.

4.1 Estimation of model results

After the model run completed the results of calculations can be visualised. Firstly the model calculation accuracy must be considered. To evaluate the model accuracy there are several statistical indicators generated by software that shows model accuracy. Mainly this is indicated by calibration residual which is calculated *vs* observed head differences (PAPER VII). The calibration residual (R_i) is defined as the difference between the calculated (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 are indicators if the calculations are under- or overestimated, value is negative or positive. To estimate calibration accuracy root mean squared error (RMS) can be also used to see the accuracy of all time 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 a calibration is said to be achieved. During several test runs of the model it was noticed that maximum difference in calculated head value at all analysed time period +/- 1.5 m would be sufficient. If the maximum difference is chosen larger then the system accuracy decreases – calculated head values are not following the trend of observed head values (Fig. 9).

Accuracy of groundwater capacities are estimated by differences of water in and outflow into defined zones. There are generated water table contours and flow direction, velocity and magnitude maps to compare expected and generated situation

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

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

Where,
qx – discharge into direction x,
Kx –hydraulic conductivity (m/d),
$\frac{\delta h}{\delta x}$ - rate of head changes in the direction x (hydraulic gradient).

When the head gradients in a model are too high then Darcy's law indicates that the modeled recharge rates are high and/or the used conductivities are necessary to increase. Adjustment of the input parameters of conductivity and storage values with example of the observation well No. A-I-1 located near the Uus-Kiviõli prospect area are described here. For the process to calibrate the model input parameters were adjusted. Model parameter adjustment is done at the situation while only one parameter is changed in time. In this condition a analyse is made with conductivity and specific storage values to achieve the lowerst error of RMS and residual R. Fig. 7 describes the variations used at conductivity at ranges 15...25. Best result with lowest RMS error of 0.44 with the conductivity value of K = 20 m/d was achieved.

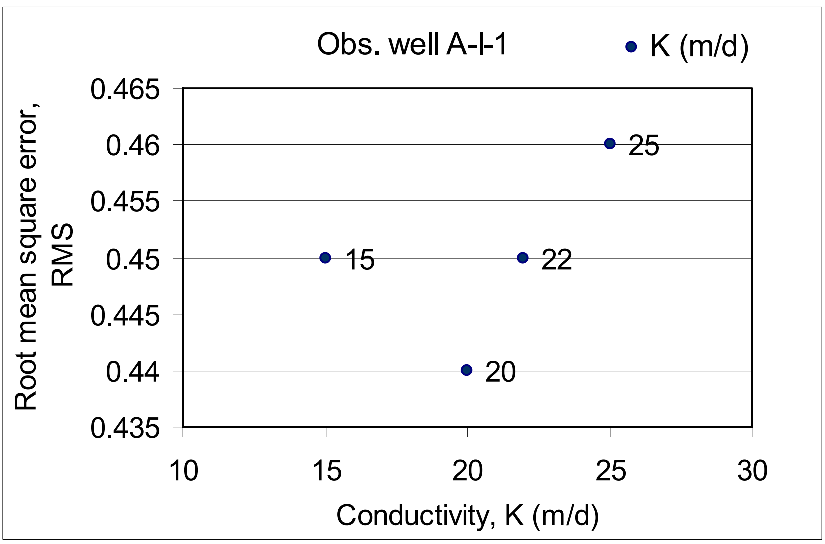

Fig. 7 Sensitivity of conductivity values effect on RMS at well No A-I-1

At transient state the storage parameters are used. Observation well analysed, A-I-1 locates at the zone where upper layer is dry and acts as confining layer. Therefore the specific storage parameter changes were tested. During analyse the RMS value did not change. Result of the variations with S_s value is given at the *Fig. 8.*

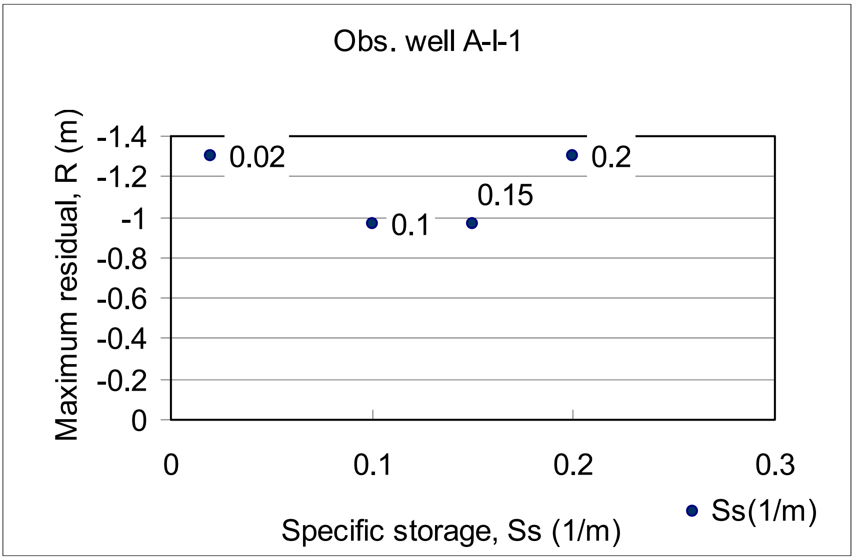

Fig. 8 Specific storage variations onto maximum residual R.

Following Fig. 9 describes the head values calculated by the software. Calculated head values with the parameter values of K=20 m/d and S_s=0.1 gave the lowest residual R=-1.08m. While there was set a scope to have maximum residual R less than +/-1.5 it can be said to have good fit of the calculated head values. Fig. 10 describes the calculated head value compared to the observed water table elevations. It can be seen that the calculated head value follows the trend of water table changes due to precipitations.

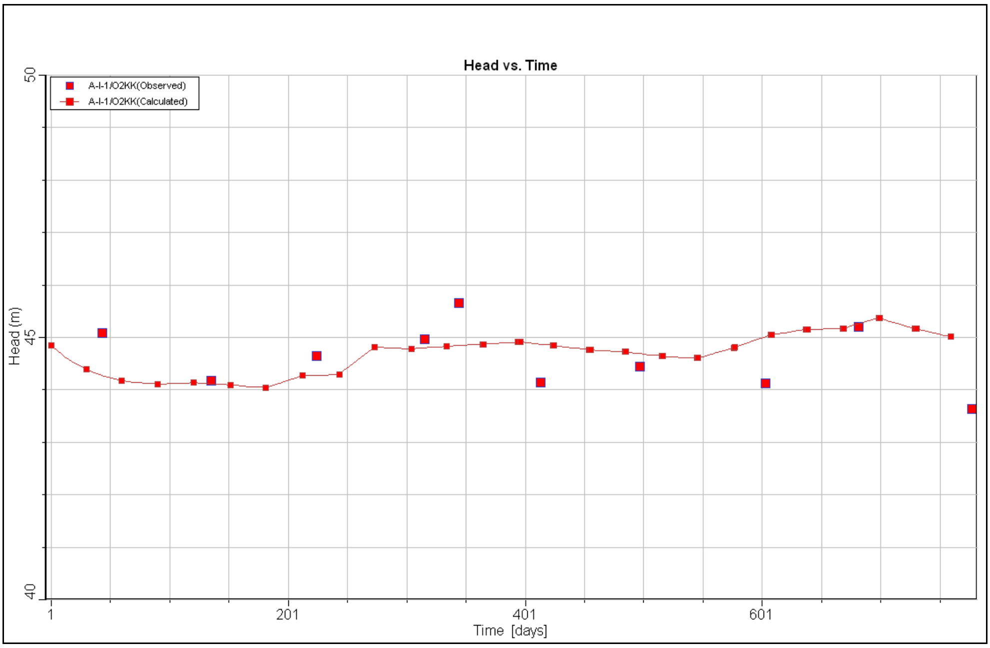

Fig. 9 Calculated and observed head values comparison after adjustment of input parameters .

Here described method with example of observation well no A-I-1 was used to adjust hydraulic properties at the all area of the model, at 28 observation wells. Model was assumed to be accurate when the root mean square RMS for the all observed values was less than +/-1.5 m; here the result 1.16 m was achieved. Model general accuracy can be estimated also by correlation coefficient. Calculated and observed head values of the model are well correlated when the coefficient is close to 1. Her described model reached the correlation coefficient 0.97 that shows both data values – calculated and observed head values) are well related. Correlation coefficient near zero is indicative of minimal or no relation between calculated and observed head values.

5. RESULTS OF THE MODEL

After model calibration and adjustment of input parameters the results of software calculations could be extracted. Herewith was analysed water flow rate from the closed Ahtme mine into Estonia underground mine as example to compare the results with previous research analytical calculations (PAPER I). To see the water flow movement, water flow velocity figure is provided at Fig. 10 as describing the situation.

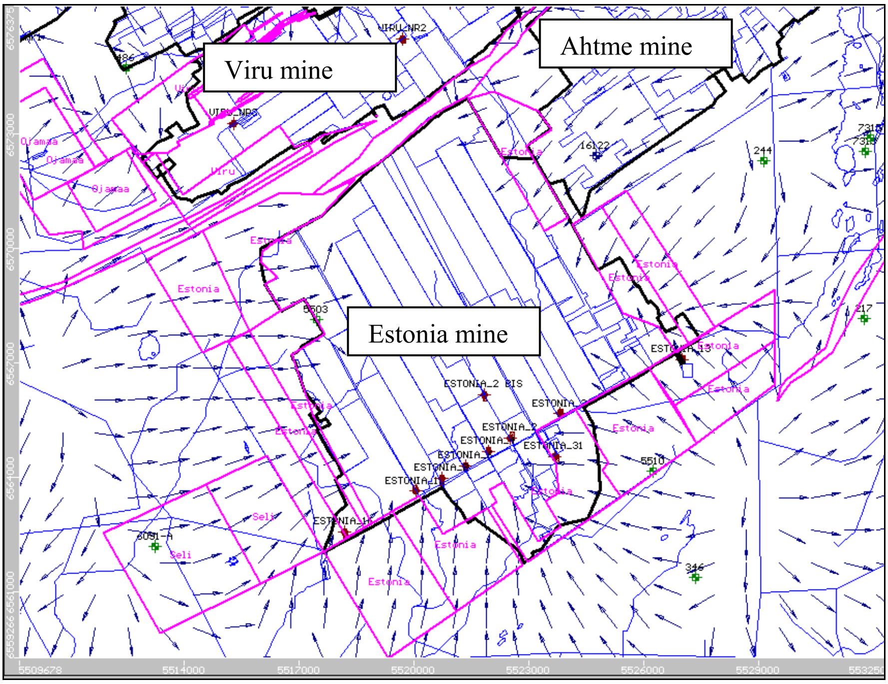

Fig. 10 Example of water inflow into working Oil shale underground mine at December 2009 (model time step 760 days)

For the estimation the budget zones – Estonia mine, Ahtme-Estonia pillar and Viru mine were defined as seen at Fig. 11.

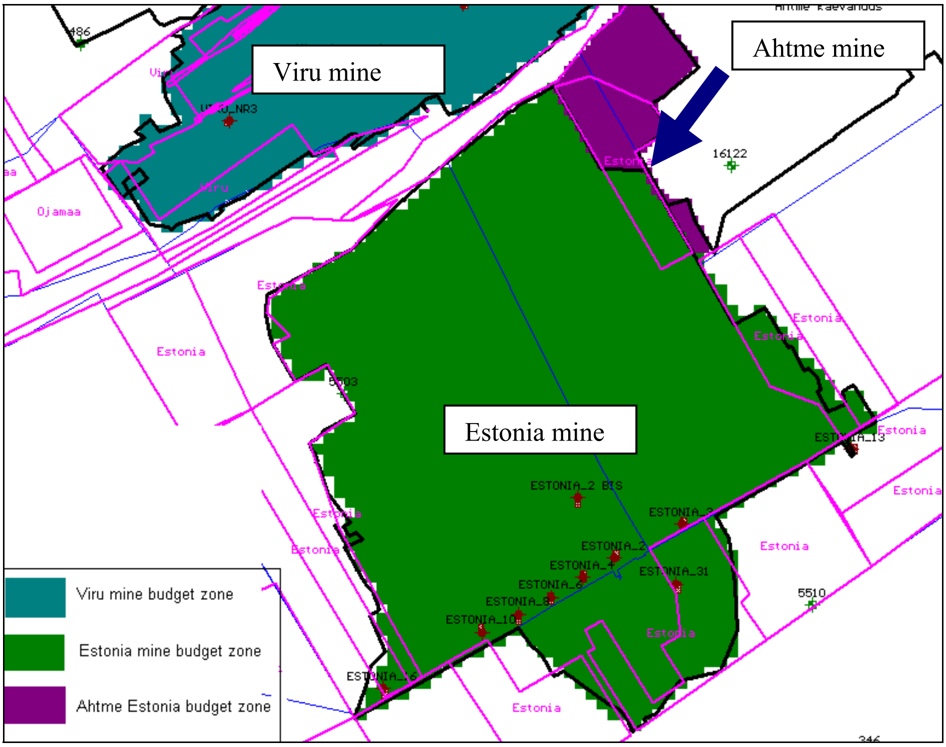

Fig. 11 Schematic picture of the defined buget zones of water in and out flow

At previous result the water exchange between the two mines was calculated analytically and was found water flow 6.48 x 10^6 m^3 annually, 17 x10^3 m^3/day from Ahtme underground mine into Estonia mine (PAPER I). Current analyse received rate of water inflow from the Ahtme mine site of 27x10^3…42.8 x 10^3 m^3/day. There was tested increase of specific storage and reduction of conductivity value at separate model runs, but the differences where insignificant – 20 to 80 m^3/day different than described first case. Following research could test a change while rate of recharge is variable. There could be calculated all the water exchange rates between the mine sites with dynamic model.

5.1 Visualisation of groundwater flow, 2 and 3 dimensional maps

Beside the results of mathematical calculations visualisation materials are given. Software provides beside the numerical values visualization material of the analysed groundwater table and its movements. Previously mentioned Fig. 10 visualises groundwater flow, directed to the Estonia underground mine. This graphical map is useful for further estimations while barrier pillar would be optimal to use and gives indicators where is the optimal location to use pillar to reduce water inflow.

As result of simulation the 3 dimensional groundwater table with contour map of water table elevations are provided, seen at Fig. 12. With the map view also the groundwater flow animation was generated (*.avi).

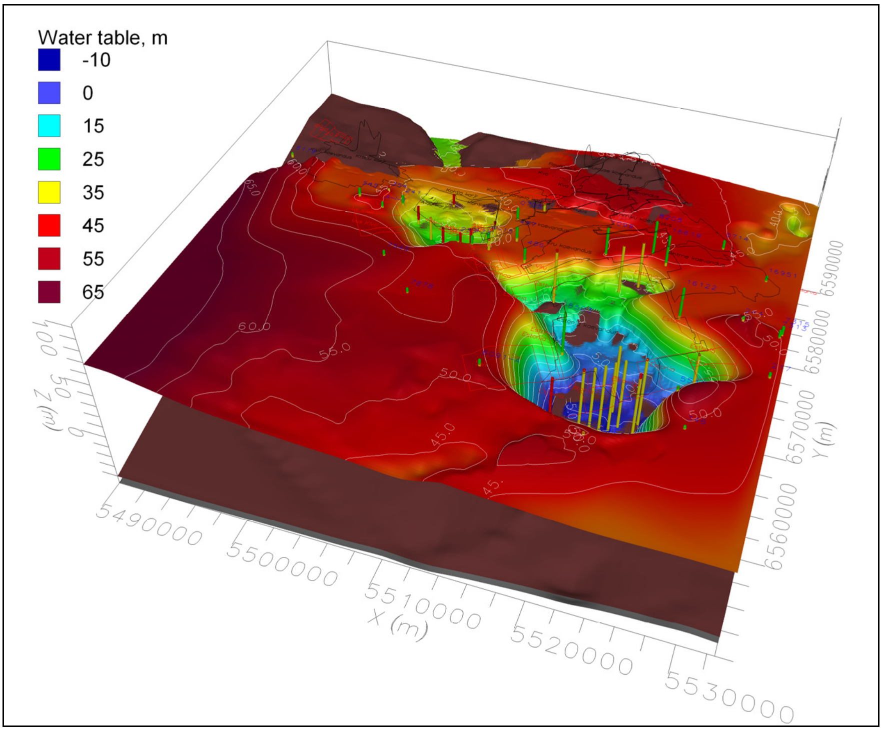

Fig. 12 Groundwater table at 3D view calculated by the software of the year 2009

6. CASE STUDY OF DEWATERING UNDERGROUND MINE

There is created experimental process of dewatering planned underground mine of Uus-Kiviõli. Uus-Kiviõli is located nearby closed Kiviõli underground mine and Aidu open cast (Fig. 9.) For the simulation it was estimated to use five pumping wells with capacity 50 x 10^3 m^3/d at the southern area as this is approximate pumping rate for underground mine dewatering. Results of the dewatering process are seen at the Fig. 13 where after 2 years pumps have been working the oil shale layer is not dewatered down to the bottom layer of oil shale. This may be indicator to have very high rate of water inflow into prospect mine.

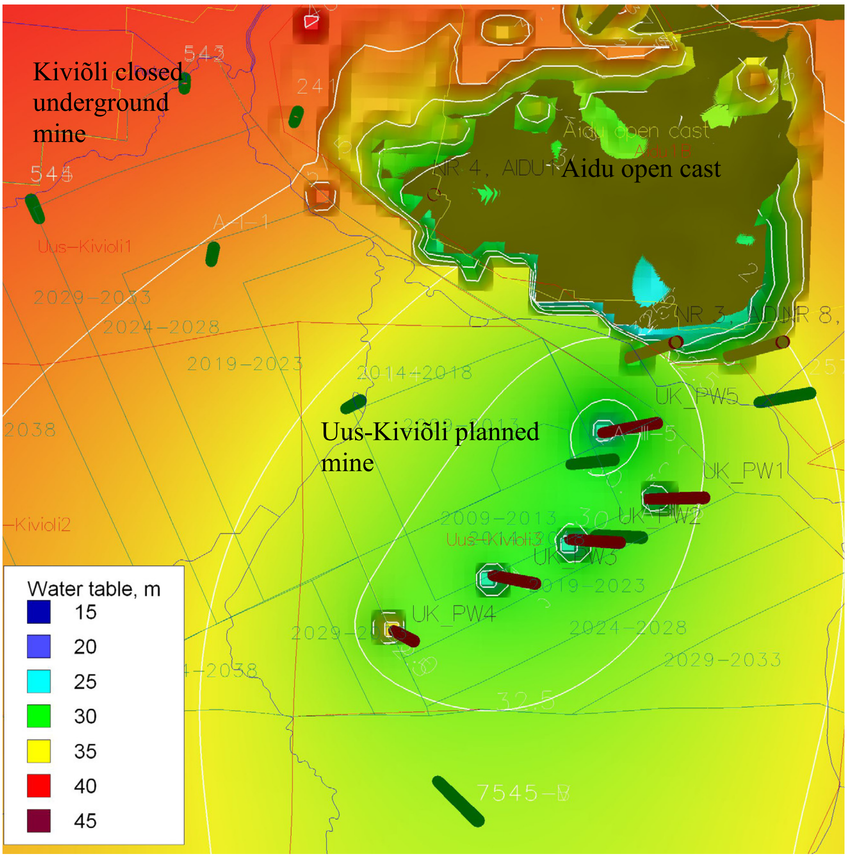

Fig. 13 Shows the result of mine dewatering simulation – depression cone formulated.

After the mine dewatering processes was tested the effect of using impermeable wall to reduce dewatering capacities of planned underground mine (PAPER VI). There was tested 5 m thick wall with conductivity 0,01 m/d. Location of the impermeable wall is chosen by knowledge from the water flow direction of main water inflow and by environmentally protected areas located at south and south-west (Fig. 14). Chosen parameters for the impermeable wall are subject to optimise and consider the technological possibilities to apply and are probably overestimated for the test case.

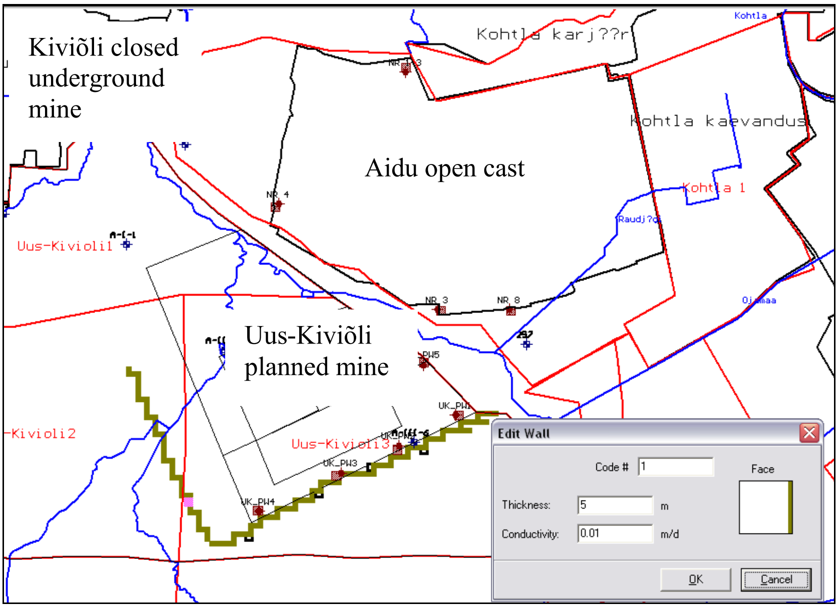

Fig. 14 impermeable wall with conductivity of 0,01 m/d and thickness 5m/d was tested (brown line at the south of Uus-Kiviõli area)

Following Fig. 15 visualises situation while the barrier pillar is used. There is seen the decrease of cone of the depression development to the southern area. From the cross sectional views it was estimated approximate cone of depression 4 km, where the initial average groundwater level recovered.

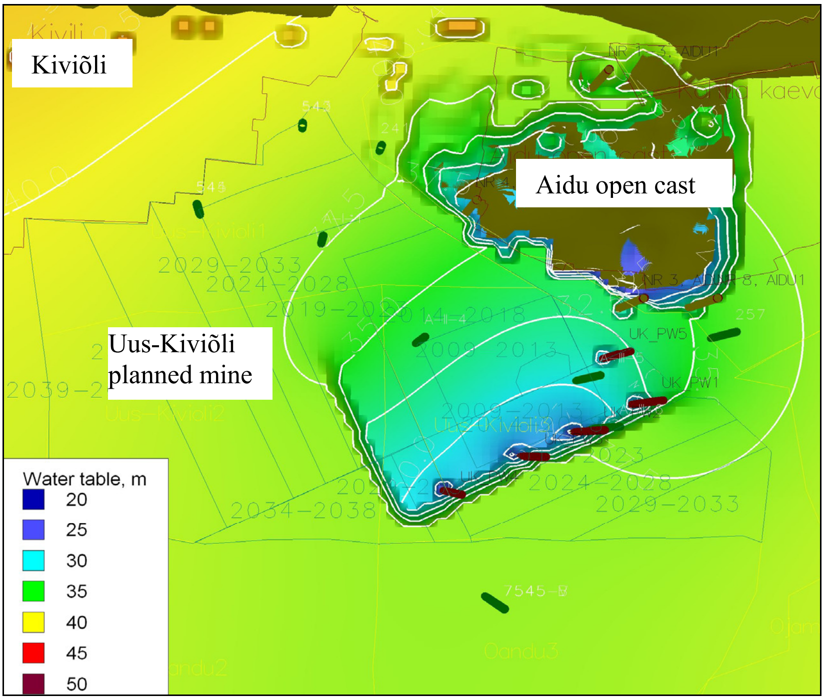

Fig. 15 Simulation with impermeable barrier used for the Uus-Kiviõli mine

7. CONCLUSION AND RECOMMENDATIONS

Groundwater modelling systems are useful tools for estimations while decisions are needed to make - location, capacity and number of pumping wells have to be chosen. While the water income is necessary to avoid decreasing dewatering impact – barrier pillars or impermeable walls can be simulated to see how thick wall and which parameters it must have, where is optimal location to have environmentally protective effect. However, modelling at geologically disturbed area as result of mining activity is rather challenging task due to software limitations and high variation of ranges of input data values. All the parameters inserted into model are affecting the results of the simulation to be achieved. Main values that influence calculation are conductivity, rate of recharge, storage values applied and layer elevations.

Current research created base model of dynamic groundwater flow, which can be used for further estimations. Modelling gives indicative parameter values suitable for the local conditions and described analyse process of choosing best fit of conductivity value and sensitivity on specific storage values. Analyse showed that at the conductivity 20 m/d with specific storage value 0.1 describes limestone layer of Uus-Kiviõli prospect area as example while the calculated head value had lowest residual R=-1.08m – maximum difference between observed and calculated water table head values.

With the parameters described Uus-Kiviõli underground mine dewatering process was simulated. Used 5 pumping stations with capacity $50x10^3$ m^3/d created approximate cone of depression 4 km, where the groundwater level elevation recovered. After the process impermeable wall was simulated – water table increase and cone of depression was restricted. Further analyse should consider simulation with technologically possible solutions.

There was analysed water inflow into working mine Estonia from the nearby located water filled Ahtme mine using dynamic flow model. Calculation by software showed inflow from closed mine Ahtme side to Estonia to be higher, with amount of $27x10^3$…42.8×10^3 m^3/day, as previously was estimated 17×10^3 m^3/day (6.48×10^6 m^3 annually) of water inflow from the closed Ahtme mine.

Beside numerical values groundwater modelling created different visualisation material like 3 dimensional views of groundwater level and it changes in time (map and video files). Also water flow directions are provided. There can be simulated scenarios of choosing different pumping station locations and capacities.

Current analyse faced during the study the limitations by the software:

- Problematic to simulate groundwater table increase for the area where the initially dry model cells occurs. Therefore would be challenging task to achieve good result of simulate groundwater table increase after the mine site is closed and starts to water fill.

- Defining the void spaces of underground mine are discussed minimal at the literature.

Results of current analyse gives suggestions for further analyses and mine site modelling at Estonian conditions:

- When the estimations with modelling are given the scenarios, for example best, worst and optimal cases would be objective to use with different input values used (conductivity and specific yield) locally.
- Following research should consider defining water filled underground mines as “general head boundary” conditions as they act as underground water pools.
- Large void spaces of mined out area could be specified as no flow cells to avoid no convergence problems of the model calculations. This assumption may have variances to the water budget calculations on measured result
- Future simulation could be run the model at predictive state
- Trace elements test could be used to validate the data used at further predictions and for modelling use.

ACKNOWLEDGEMENTS

Current research is done under framework of Estonian Scientific Fund research ETF 7499 “Conditions of sustainable mining” where one of the scopes is to compose methodology of natural resources usage, including criteria of computational modelling.

The author thanks supervisor Prof. Ingo Valgma, consultant Prof. Enno Reinsalu from TTU Department of Mining giving the knowledge and good ideas. Also I thank Andrus Paat, Kalmer Sokman, Allan Viil from Eesti Energia Mining Company, Tauno Tammeoja from Ojamaa Mining Company providing initial data for the research. Thanks to my brother Hendrik Lind a programme for observation well database was created.

I am very thankful to my family – Oliver and daughter Emilia Beatrice who where very patient and supportive during my studies.

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GROUNDWATER FLOW MODEL OF THE WESTERN PART OF THE ESTONIAN OIL SHALE DEPOSIT

Abstract

In the following decade there are expected changes in groundwater regime while new prospect mines are under interest to open – Uus-Kiviõli and Ojamaa mines. Oil shale resources at Aidu and Viru area finish the mine sites will be closed and flooded. Therefore the groundwater table increases at closed sites and will be decreased at prospect areas. To estimate and visualise the situation computational groundwater flow modeling has been applied at most of the cases to give estimations for future situation.

Current analyse created base model at the dynamic regime for the further possible estimations needed. The research analysed conductivity and storage parameters as a procedure to reach acceptable model accuracy. Analyse showed that conductivity parameter adjustment decreased the average error at modelled time period and specific storage as parameter to describing the rock mass water release ability, decreased the maximum residual value of the modelled time period. To see the general model accuracy the software provides the confidence level described by the correlation coefficient. The coefficient close to 1 shows good relation between calculated and observed head value. While the value reaches close to 0 - minimal or no relation is between described values. Created base model of oil shale deposit achieved correlation coefficient 0.97 with measured head values of 28 observation well.

Analyse of water exchange between closed Ahtme and Estonia underground mines were tested. Calculation by software showed inflow from closed mine Ahtme to Estonia to be higher than previous analyse by classical calculations:
$27 \times 10^3 \ldots 42{,}8 \times 10^3$ m^3/day.

As a case study underground mine dewatering process and barrier pillar usage to decrease the cone of depression was visualised.

EESTI PÕLEVKIVMAARDLA LÄÄNEALA VEEREŽIIMI MUDEL

Kokkuvõte

Põlevkivi kaevandamisel Ida-Virumaal on lähikümnendil oodata veerežiimi mõjutavaid muudatusi. Ojamaa mäeeraldisel teeb Ojamaa Kaevandused OÜ kaevanduse avamiseks läbindustöid, AS-il Eesti Energia Kaevandused on kavas sulgeda Aidu karjäär ja Viru kaevandus, kus maavaravarud on ammendumas, käimas on Uus-Kiviõli (Maidla) kaevanduse keskkonnamõju hindamine. Kaevanduste sulgemisel täituvad alad veega, uute kaevanduste rajamiseks on vaja veetase alandada. Selleks et hinnata ja visualiseerida tuleviku olukorda, kasutatakse enamasti põhjavee modelleerimise võimalusi.

Käesolev uurimus koostas dünaamilise põhjavee režiimi baasmudeli edaspidiste hinnangute ja stsenaariumite loomiseks. Uurimistöös esitatakse hüdrogeoloogiliste lähteandmete kohandamise valikuid, kui üht osa kalibreerimise protsessist. Analüüsi tulemusel oli näha veejuhtivuse (m/ööp) parameetri kohaldamisel lubatud piirvahemikus kogu mudeli üldise, keskmise vea vähenemist arvutusliku ja tegeliku veetaseme osas. Veeloovutusteguri kohaldamisel vähenes aga maksimaalne erinevus arvutusliku ja tegeliku vahel. Selleks et hinnata mudeli adekvaatsust üldiselt, koostab tarkvara mudeli usaldusväärsuse ja korreleerumise statistilised väärtused. Korrelatsiooni koefitsient ehk arvutuslike ja tegelike veetasemete kokkusobivus esitatakse kogu mudeli ajalise perioodi lõikes. Koefitsient lähedane väärtusele 1 kirjeldab mudeli võimet arvutada tegelikele mõõdetud veetasemete väärtustele lähedane tulemus. Mida väiksem see väärtus on, 0 või sellele lähedane, seda vähem modelleerimise tulemused vastavad looduslikule olukorrale. Käesolev põlevkivimaardla lääneala baasmudel saavutas hea korreleerumise tulemuse – 0.97, mis on saadud 28 vaatluskaevu mõõtmistulemuste ja arvutuslike veetaseme väärtuste võrdlemisel. Mida enam on veeseire vaatlusandmeid, seda adekvaatsemaks saab modelleeritava ala luua, kuna veetasemete mõõtmised aitavad kinnitada mudeli käitumist tegelikule.

Töös analüüsiti vee juurdevoolu suletud Ahtme kaevandusest töötavasse Estonia kaevandusse. Arvutused näitasid suuremat vee juurdevoolu kui varasemad arvutused (17 x 10^3 m^3/ööp), olles vahemikus 27 x 10^3…42.8 x 10^3 m^3/ööp.

Töös koostati simulatsioon veetaseme alandamise kohta perspektiivse Uus-Kiviõli allmaakaevandamise alal. Protsess veetaseme alanemise ja seejärel tõkketerviku kasutamisega esitati käesolevas töös.

PAPER I Reinsalu, E.; Valgma, I.; **Lind, H**.; Sokman, K. (2006). Technogenic water in closed oil shale mines. Oil Shale, 23(1), 15 - 28. Estonian Academy of Publishers

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PAPER III Valgma, I.; **Lind, H**.; Erg, K.; Sabanov, S. (2007). The future of oil shale mining related to the mining and hydrogeological conditions in the Estonian deposit. In: 4th International Symposium "Topical problems of education in the field of electrical and power engineering". Doctoral school of energy and geotechnology. [Proceedings volume 1] : Kuressaare, Estonia, January 15-20, 2007: 4th International Symposium "Topical problems of education in the field of electrical and power engineering", Kuressaare, January 15-20, 2007. (Toim.) Lahtmets, R.. Tallinn: Tallinn Technical University, 2007, 104 - 107.

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