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HYDROGEOLOGY MODEL OF IGNALINA REGION FOR VISAGINAS WELL FIELD PROTECTION ZONE SUBSTANTIATION

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Abstract. IAEA safety documents (Safety standarts… 1994; 1999a; 1999b) recommend assessing the safety framework of groundwater exploitation in the proximity of nuclear facilities. The main task of this study is to assess the results on the re-calculation of Visaginas town wellfield well protection zones (WPZ), since the Visaginas town wellfield is installed close to Ignalina Nuclear Power Plant (INPP) site and other sites of existing or planed new nuclear facilities. The numerical model used in this study is based on three-dimensional finite-element code FEFLOW 5.0 which allows modeling of groundwater flow and contaminant transport in a layered three-dimensional system. The calibrated model of Visaginas wellfield area simulated the groundwater flow in the Quaternary and Upper-Middle Devonian aquifers systems. The evaluation of well protection zones for wellfields exploiting groundwater is currently determined by the Lithuanian legal documents (HN 44:2006). As a result of modeling the groundwater formation sources were specified and dimensions of wells protection zones in sectors 3^a and 3^b were established. The groundwater modeling results of this study shows that the third sub-zone (3^b) of WPZ should be 0.6-1.1 km away from the wellfield fence. The long axis of WPZ extends for 4 250 m from north to south and for approximately 3 250 m from east to west. Visaginas wellfield capture zone during 50 years operation would reach the site for planned near-surface repository for radioactive waste in case of hypothetical very high wellfield capacity more than 70 000 m^3/day.

Key words: wellfield, capture zone, aquifer, finite elements model.

1. Introduction

In 2002, the Government of Lithuania approved the adoption of the ‘‘immediate dismantling’’ strategy for decommissioning of both Ignalina NPP units. A key component of this decommissioning strategy is to dispose of operating and decommissioning radioactive waste (RW) in a near-surface repository (NSR). Except the NSR other nuclear facilities are and will be installed in industrial site of Ignalina NPP in course of time. The main facilities are following (Fig 1): existing RW storage facilities, existing spent nuclear fuel (SNF) dry storage facility; planed solid waste management and storage facilities, planed SNF dry storage facility, planed landfill facility for short-lived very low-activity RW.

IAEA safety documents (Safety standarts… 1999a; 1999b; 1994) recommend assessing the safety margins of groundwater supply in the areas next to nuclear facilities. The Lithuanian Hygiene Standard (HN 44:2006) obliges to establish well protection zones (WPZ) of three sub-zones for wellfields exploiting the groundwater resources.

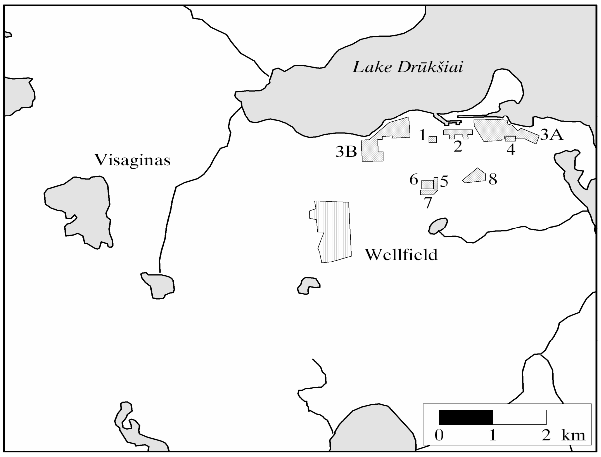

Fig 1. Study area with the sites of main existing and planed nuclear facilities in the Ignalina NPP industrial site: 1 – existing operational RW storage facilities; 2 – Ignalina NPP; 3A and 3B – sites for the planed new NPP; 4 – existing SNF storage facility; 5 – planed SNF storage facility; 6 – planed facilities for the solid waste management and storage; 7 – planed landfill facility for short-lived very low-activity RW; 8 - planed NSR

According to wellfields classification, the Visaginas wellfield belongs to group II_b^1. The wellfields attributed to this group are in relatively open multi-layered aquifers systems, where productive aquifer is confined from the top by thin, locally spread low permeable layers. The main requirements regarding wellfields of II_b^1 group protection zones are listed in Table 1.

Table 1. Main requirements of Lithuanian Hygiene Standard HN 44: 2006 (HN 44:2006) regarding the wellfields of group II_b^1

II_a^2, II_b^1, II_a^1 groups wellfields	**Requirements**
1st sub-zone	
Distance from groundwater withdrawal installations	> 10 m
2nd sub-zone	
Boundary for unconfined groundwater	Travel path length over 400 days
Boundary for confined groundwater	Travel path length over 200 days
3rd sub-zone	
Boundary for unconfined groundwater (3^a)	Capture zone over 25 years
Boundary for confined groundwater (3^b)	Capture zone over 25 years

The main task of the present study is applying computer code FEFLOW to substantiate the WPZ limitations of existing Visaginas wellfield with the maximal predicted (and permitted) wellfield pumpage rate of 31 000 m^3/day and to answer whether nuclear facilities of Ignalina NPP industrial site is out of WPZ of Visaginas wellfield. The present study area was the territory of the Ignalina NPP region which was undergone the complex geological-hydrogeological mapping at a scale 1:50 000 and which was attributed to groundwater flow modeling of 2003 (Visagino m… 2003).

2. Methods

The geological settings, geomorphologic and other features allow distinguishing two aquifer systems in the groundwater active circulation zone of the region: the Quaternary aquifers system and the Upper-Middle Devonian aquifers system (Table 2).

In a regional context, the Quaternary aquifer system that contains unconfined aquifer and a series of semi-confined and confined aquifers attributed to intertill deposits of different interglacial periods is the first water-bearing hydrogeological system from the top in the Ignalina NPP region. In the present study, the two uppermost Quaternary aquifers are treated as semi-confined due to often very small height of hydraulic head above the top boundary of the aquifer. The remaining four Quaternary aquifers are confined with hydraulic head clearly above the top boundary of aquifers. The Upper-Middle Devonian aquifer system is a classical confined system with high hydraulic head above the top boundary and is composed of many sub-layers of different hydraulic conductivity.

Table 2. Description of the geologic units forming groundwater active circulation zone in the region (Visagino m… 2003)

Geologic unit	Maximum thickness, m	Lithology	Water bearing characteristics
Till deposits Baltija	15	Clayey and sandy loam	Aquitard
Intertill deposits (aglllbl-gr)	25	Interbedded sand and gravel	Very minor aquifer
Till deposits Grūda	20	Clayey and sandy loam	Aquitard
Intertill deposits agIII-IIgr-md	23	Interbedded sand and gravel	Very minor aquifer
Till deposits Medininkai	30	Clayey and sandy loam	Aquitard
Intertill deposits (agllmd-žm)	74	Interbedded sand and gravel	Minor aquifer
Till deposits Žemaitija	40	Clayey and sandy loam	Aquitard
Intertill deposits (agll-Ižm-dn)	93	Interbedded sand and gravel	Minor aquifer
Till deposits Dainava	50	Clayey and sandy loam	Aquitard
Intertill deposits (agldn-dz)	128	Interbedded sand and gravel	Minor aquifer
Till deposits Dzūkija	25	Clayey and sandy loam	Aquitard
Till underlaying deposits (agldz)	30	Interbedded sand and gravel	Minor aquifer
Upper-Middle Devonian terrigenic formation (D_{3+2}šv-up)	136	Interbedded sand, weak cemented sandstone, aleurollite and clay	Major aquifer
Middle Devonian carbonatic formation (D_2nr)	80	Interbedded clay, clayey dolomite and domerite	Aquitard

To implement the finite-element model based on FEFLOW, the territory of complex geological-hydrogeological mapping survey at a scale 1:50 000 completed in 1995 (Отчет о… 1995) was discretized into a finite-element grid with 150 318 mesh elements and minimal step of 20 m in the areas close to the Visaginas wellfield and with the maximal step of 1200 m in the domain periphery. The domain area was of 1300 km^2. The model was vertically discretized into 7 active layers as was derived from the regional hydrogeological features (Visagino m… 2003) (Fig 2, Table 3).

Here we briefly discuss the formulation of boundary conditions specified in the FEFLOW code. Different types of boundary conditions may be expressed by the different equations (Diersch 2002).

Table 3. Hydrogeological schematization of the studied region for groundwater flow modeling

Observed hydrogeological features			Schematized hydrogeological features	
Geologic unit	Lithology	Water bearing characteristics	Simulated layers	Water bearing characteristics
Unconfined aquifer	Various	Very minor aquifer	1 layer	Unconfined aquifer
Till deposits Baltija	Clayey and sandy loam	Aquitard	2 layer	Low permeable
Intertill deposits (aglllbl-gr)	Interbedded sand and gravel	Very minor aquifer		
Till deposits Grūda	Clayey and sandy loam	Aquitard		
Intertill deposits agIII-IIgr-md	Interbedded sand and gravel	Very minor aquifer		
Till deposits Medininkai	Clayey and sandy loam	Aquitard		
Intertill deposits (agllmd-žm)	Interbedded sand and gravel	Minor aquifer	3 layer	Confined aquifer agllmd-žm
Till deposits Žemaitija	Clayey and sandy loam	Aquitard	4 layer	Low permeable
Intertill deposits (agll-Ižm-dn)	Interbedded sand and gravel	Minor aquifer	5 layer	Confined aquifer agll-Ižm-dn
Till deposits Dainava	Clayey and sandy loam	Aquitard	6 layer	Low permeable
Intertsill deposits (agldn-dz)	Interbedded sand and gravel	Minor aquifer	7 layer	Main confined aquifer
Till deposits Dzūkija	Clayey and sandy loam	Aquitard		
Till underlaying deposits (agldz)	Interbedded sand and gravel	Minor aquifer		
Upper-Middle Devonian terrigenic formation (D_{3+2}šv-up)	Interbedded sand, sandstone, aleurolite and clay	Major aquifer		
Middle Devonian carbonatic formation (D_2nr)	Interbedded clay, clayey dolomite and domerite	Regional aquitard	Lower model boundary	Not permeable

For the Quaternary aquitards there were set 2nd kind boundary conditions for all simulated layers, Q=0 (impermeable boundary). The same boundary condition was also set within those boundaries of the model, in the Upper-Middle Devonian aquifer, coincident with the groundwater flow path lines. In the remaining lateral boundaries of productive aquifer, the 1st kind boundary condition was set.

The upper or surface boundary of the aquifer system is usually the most complex and was specified as 2nd kind boundary condition – water level of the lakes and rivers and the variable recharge rate.

The lower boundary of the model is the top boundary of the Middle Devonian (D_2nr) regional aquitard with the boundary condition Q=0. The operation wells of the productive Upper-Middle Devonian aquifers system are simulated as 4th kind boundary condition. They represent time variable pumpage rates from Visaginas wellfield (Fig 3). Main features of model implemented by FEFLOW are described in Table 4.

Hydraulic parameters of aquifers and low permeable layers derived from groundwater flow model calibration are presented in Table 5.

In the present study, the main calibrated parameter values from the (Visagino m… 2003; Lietuvos požeminės… 2004b; Supplemented Environmental… 2007) for groundwater flow modeling by FEFLOW code have been used. For particular sites related to different activities of Ignalina NPP the parameters where they do exist were included into present modeling case.

Table 4. Features of the FEFLOW numerical model for the domain of Visaginas wellfield

Feature	Characterization
Problem class	Separate flow process
Time class	Transient (unsteady) flow
Time stepping scheme	Adams-Bashforth/Trapezoid rule predictor-corrector
Vertical exaggeration	1:1
Problem measure	49519.34 m
Number of layers	7
Number of slices	8
Type	Saturated
Dimension	Three-Dimensional
Element type	6-noded triangular prism
Mesh elements	150 318
Aquifers	Confined
Error tolerance	$1{\cdot}10^{-2}$ applied to Euclidian L_2 integral (RMS) norm
Maximum number of iterations per time step	12
Adaptive mesh error	$1{\cdot}10^{-2}$
A posteriori error estimator	Onate-Bugeda algorithm
Mesh nodes	86 576
Mesh optimization	not done

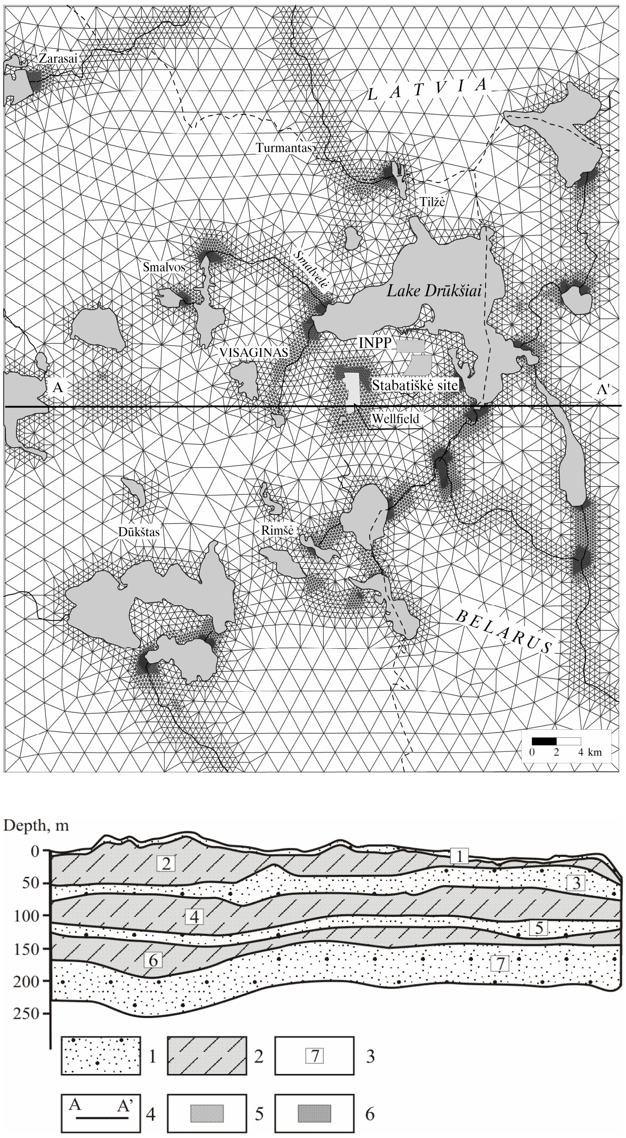

Fig 2. Finite-element grid and simulated layers used for the model domain of Visaginas wellfield area in present study: 1 – aquifers (in cross-section); 2 – low permeable layers (in cross-section); 3 – number of model layer; 4 – cross-section line; 5 - wellfield area; 6 - Ignalina NPP site

Fig 3. Pumpage rate from the Visaginas wellfield in 1978-2009 (based on the data reported in (Galimybių laidoti… 2005; Vandens srautų… 2006; Lietuvos požeminės… 2004a; 2005; 2006; 2007; 2008)

Table 5. Hydraulic parameters of aquifers and low permeable layers derived from groundwater flow model calibration (Visagino m… 2003)

Aquitards	**Hydraulic conductivity, m/day**	
	Prevailing area	**Close to INPP and wellfield**
Between unconfined aquifer and agllmd-žm	$1{\cdot}10^{-4}$-$8{\cdot}10^{-4}$	$4{\cdot}10^{-4}$
Between agllmd-žm and agll-Ižm-dn	$1{\cdot}10^{4}$ - $1\ 10^{-3}$	$1{\cdot}10^{-4}$
Between agll-Ižm-dn and D_{3+2}šv-up	$7{\cdot}10^{-5}$-$1{\cdot}10^{-3}$	$1{\cdot}10^{-4}$
Aquifers	**Prevailing area**	**Close to INPP and wellfield**
Between unconfined aquifer and agllmd-žm	1.5-10	2-7
Between agllmd-žm and agll-Ižm-dn	2-4	4
Between agll-Ižm-dn and D_{3+2}šv-up	5.5	5.5

In the FEFLOW code dimensionless storativity parameter is used which reflects approximately the aquifers compressibility measure and is expressed as the product of specific storage and aquifer thickness (Table 6).

Table 6. Additional parameters used in model case (Visagino m… 2003; Lietuvos Respublikos… 2004b; Supplemented Environmental … 2007)

Aquifer	Model layer No.	Storativity	Porosity	Bulk density, g/cm^3
Unconfined groundwater	1	0.2	0.2	2.1-2.14
Quaternary (agIImd-žm)	3	0.002	0.1-0.2	2.1
Quaternary (agII-Ižm-dn)	5	0.000153	0.11-0.13	2.1
Upper-Middle Devonian (D_{3+2}šv-up)	7	0.000187	0.15	2.3-2.5

3. Results

The calibrated model of Visaginas wellfield area simulated the groundwater flow in the Quaternary and Upper-Middle Devonian aquifers systems for the modeling period from January 1978 through to December 2009. In the first modeling stage, the groundwater flow in steady-state conditions, i. e. potentiometric surfaces in all simulated aquifers existed before the operation of the Visaginas wellfield, were recovered. The steady-state potentiometric surface of the productive Upper-Middle Devonian aquifers system is presented in Fig 4. In the second stage, potentiometric surface of productive Upper-Midle Devonian aquifers system for 1987, when actual pumpage rate from the wellfield was maximal (approximately 26 000 m^3/day), was restored (Fig 5). During the assessment of the impact of pumpage from the Visaginas wellfield on the groundwater flow, the steady-state groundwater level from first modeling stage was specified as an initial head condition.

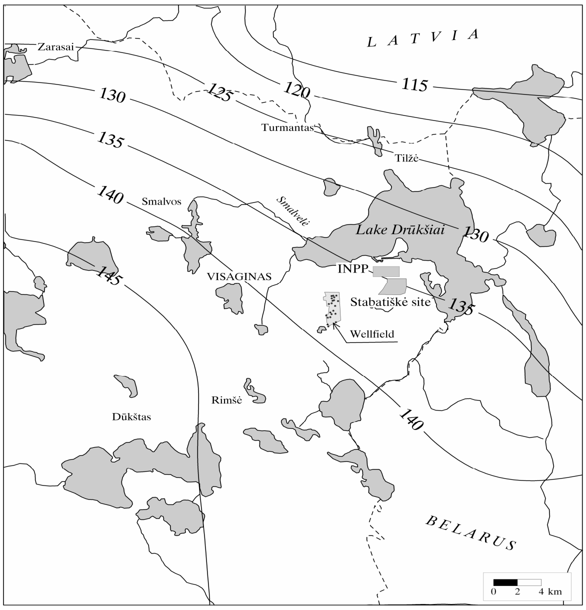

Fig 4. Simulated groundwater level (altitude, m a.s.l.) of Upper-Middle Devonian aquifer before Visaginas wellfield operation (7 layer)

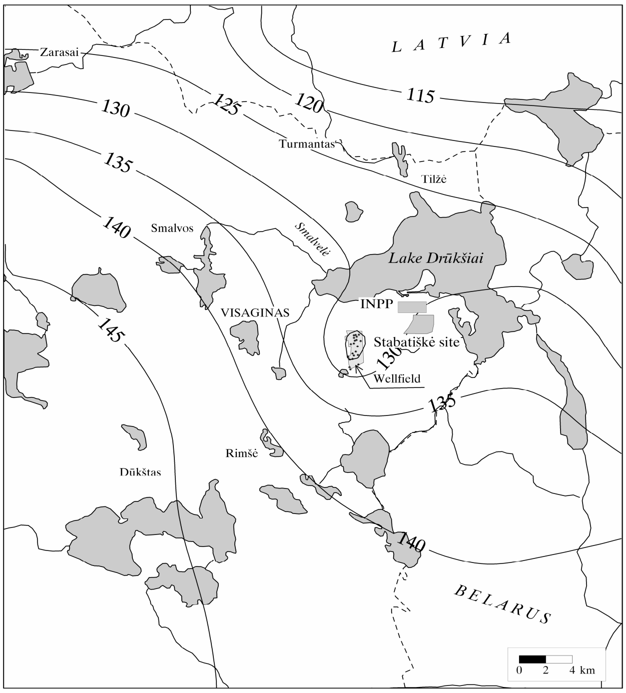

Fig 5. Simulated groundwater level (altitude, m a.s.l.) of Upper-Middle Devonian aquifer in 1987 (7 layer) (actual pumping rate of 26 000 m^3/day)

The simulated by FEFLOW groundwater levels at selected observation wells in Devonian aquifers system of the Visaginas wellfield area are given in Fig 6.

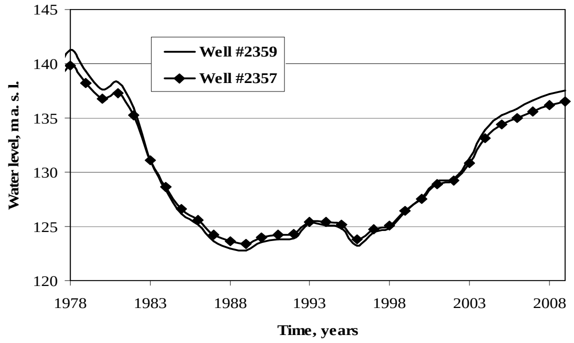

Fig 6. Simulated groundwater levels of Devonian aquifers system in Visaginas wellfield during operation period

Model predictions of groundwater flow in present study were fulfilled for the one Visaginas wellfield operation case, when wellfield is operated with the pumpage rate of 31 000 m^3/day (water demands for first stage of Ignalina NPP development).The groundwater level in the Upper-Middle Devonian aquifers system in wellfield centre, in case of the pumpage rate of 31 000 m^3/day, will decrease till the altitude of 120-110 m a. s. l. The distribution of hydraulic heads in the Upper-Middle Devonian aquifers system for hydraulic stress conditions invoked by prognostic pumpage rates are presented in Fig 7.

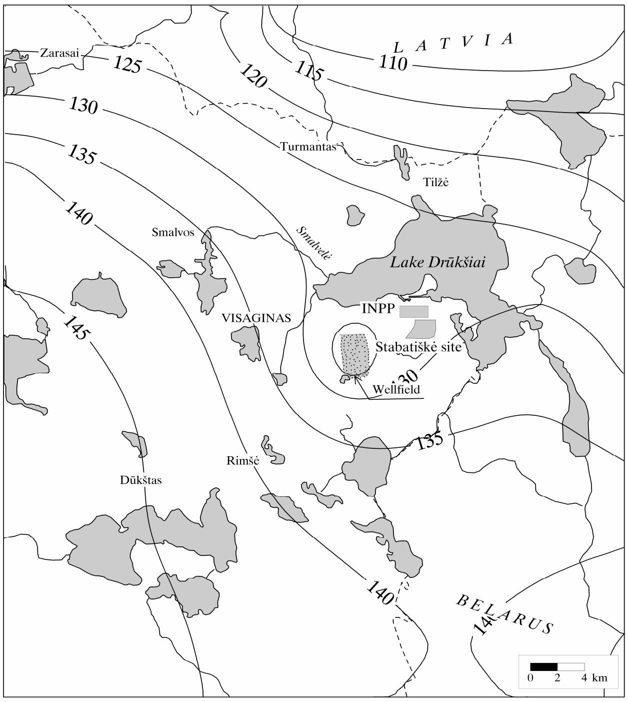

Fig 7. Simulated groundwater level (altitude, m a. s. l.) of Upper-Middle Devonian in Visaginas wellfield area (7 layer) (predicted pumping rate of 31 000 m^3/day after 50 years period)

The predicted drawdown (17 m) of groundwater for Upper-Middle Devonian aquifers system is less than the maximal permissible (69.4 m), therefore the safe yield of groundwater abstraction is ensured.

The backward tracking endpoint analysis based on potentiometric surfaces of simulated aquifers is a routine tool implemented in FEFLOW software and it was used for wellfield capture areas mapping in the present study. The endpoints, wherein the water particles complete their transport path through 25 and 50 years, outline the limits of wellfield catchment.

After 25 years operation of the wellfield with the yield of 31 000 m^3/day, its catchment boundary for productive Upper-Midle Devonian aquifer will be located at a distance of about 420-640 m, and after 50 years operation of the wellfield with the same yield – 800-1140 m from the wellfield (Fig 8).

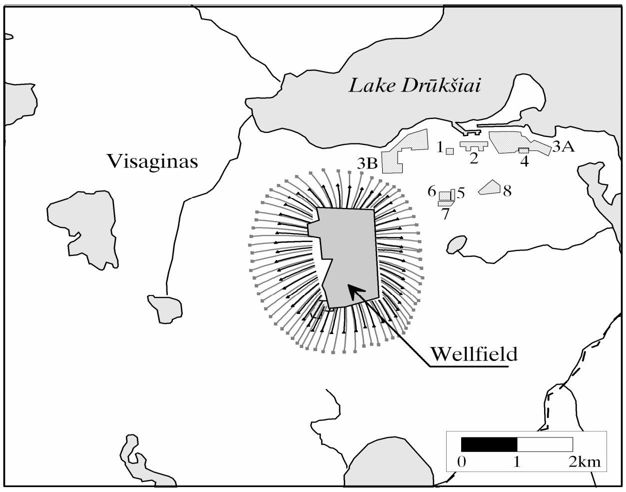

Fig 8. Modeled 3^b sub-zone of Visaginas wellfield WPZ (7 layer) (pumping rate of 31 000 m^3/day) after 25 (black lines) and 50 years (grey lines) operation (nuclear facilities in the INPP industrial site are presented in the Fig 1)

Catchment boundary of Visaginas wellfield can reach the Stabatiškė site for near surface repository only in case when wellfied is operated with the yield more then 70 000 m^3/day (Table 7).

Table 7. Predicted distance from wellfield capture zone boundary to the the site for planned near-surface repository for radioactive waste site assuming hypothetical yield implemented as a single large well after 50 years operation period

Wellfield yield, m^3/day	Distance from capture zone boundary to NSR site, m
31 000	1 310
40 000	1 080
45 000	765
50 000	600
55 000	465
60 000	315
65 000	180
70 000	60
75 000	0

In FEFLOW there are possibilities to quantify the groundwater budget, i.e. to compute the water masses entering or exiting the simulated region, sub-regions or boundary sections, using budget analyzer options. As derived from the FEFLOW simulation in the present study, the groundwater flow budget in the Visaginas wellfield capture area formed in the productive Upper-Middle Devonian aquifer during the 50 years wellfield operation period is presented in Table 8.

Table 8. Simulated by FEFLOW groundwater budget in the productive Upper-Middle Devonian aquifer for capture zone forming during the 50 years operation period when Visaginas wellfield is operated with the pumpage rate of 31 000 m^3/day

Flux in, m^3/day		Flux out, m^3/day	
Total integral flux in through capture zone	27 000	Pumpage rate	31 000
Total integral downward flux	2 300		
Total	29 300		

The groundwater budget of the whole model domain for Visaginas wellfield operation case is presented in the Table 9.

Table 9. Groundwater budget forming for the whole model domain simulated by FEFLOW during 50 years operation period when wellfield is operated with the pumpage rate of 31000 m^3/day

Flux in, m^3/day		Flux out, m^3/day	
Flux through outer and inner boundaries	4770000	Fluxes through outer and inner boundaries	4820000
Areal fluxs due to infiltration recharge	81700	Withdrawals through single wells	31000
Imbalance			265

The main source of groundwater operational yield is lateral groundwater flux of the productive Upper-Middle Devonian aquifer to the wellfield catchment area. At the pumpage rate of 31 000 m^3/day over 50 years, the lateral flux contributes 87 % of the wellfield yield. The total vertical downward flux from the capture zones in the overlaying Quaternary aquifers (agII-Ižm-dn, agIImd-žm, and unconfined aquifer), which will discharge from these aquifers within 50 years, makes 13 % of operational yield.

In order to effectively utilize groundwater flow modeling results, an understanding of the modeling limitations is essential. The groundwater flow model simulates only the movement of freshwater through the Quaternary aquifers and the Upper-Middle Devonian aquifers flow system. The implemented models are limited by simplification of the conceptual model of a complex flow system, by space and time discretization effects, by the availability of measurements for estimating spatial variation in hydraulic properties, by limitations in the accuracy of land-surface, water level altitudes, top and bottom surface altitudes of aquifers and aquitards, by the availability of water level measurements in all considered aquifers, by limitations in the accuracy of pumpage estimates, etc. There are evidences (from isotope hydrology data) that the unconfined aquifer and two semi-confined Quaternary aquifers can be discharged to local hydrographical network (Gruntinio vandens…

2005; Jakimavičiūtė *et al.* 1999; Отчет о ... 1995).

Because pumpage from Visaginas wellfield and other operational wells will probably change implementing in near future new nuclear activities in the region, consideration should be given to establishing a technically sound water-use data and water level data collection for the whole region to complement the water level measuring effort that has been not regular so far.

4. Conclusions

1. The Visaginas town wellfield operates the very productive Upper-Middle Devonian aquifers system the main water-bearing layers of which are lying at a depth of more than 80 m. The overlaying Quaternary aquifers system is composed of 3-4 main sub-aquifers, including the unconfined one. Quaternary aquifers contribute to forming the groundwater yield of the main productive Upper-Middle Devonian aquifer at small scale (13 % of operational yield).
2. For stage I of the Ignalina NPP development there were explored and licensed groundwater resources with safe yield of 31 000 m^3/day. It has been agreed by the regulating institutions and operator that the pumpage rate from the Visaginas wellfield would not exceed 31 000 m^3/day in the future.
3. Based on the Visaginas wellfield prospecting, exploration and operation data, and data of complex geological-hydrogeological mapping survey at a scale 1:50 000, the groundwater flow model including detailed representation of Visaginas wellfield site was compiled already in 2003 (Visagino m… 2003). As a result of that modeling, the groundwater formation sources were specified and dimensions of WPZ 3^a and 3^b sectors were established. It was concluded that the wellfield groundwater yield is formed by lateral very high flow rate in the same productive aquifer which governs relatively small dimensions of protection zones.
4. In 2010, a version of the new groundwater flow model of Visaginas wellfield area was implemented for the NSR site revalidation. The groundwater modeling results of the present study evidenced that the previous results (Visagino m… 2003) are acceptable and justified and the WPZ for Visaginas wellfield complies with Hygiene Standard requirements and it should not be changed.
5. Visaginas wellfield capture zone after 50 years operation period would reach the site for a near-surface repository for radioactive waste in case of hypothetical very high wellfield capacity more than 70 000 m^3/day.

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Отчет о проведенной комплексной геолого-гидрогеологической и инженерно-геологической съемке масштаба 1:50 000 в районе Игналинской АЭС на территории листов N-35-5-Г-в,г, N-35-6-В-б,г, N-35-17-Б, N-35-18-А, N-35-17-Г-а,б, N-35-18-В-а,б, в пределах Литвы и Белоруссии, с доизучением геолого-гидрогеологических и инженерно-геологических условий в пределах Латвии. (Дукщяйский обьект). [Hydrogeological and engineering-geological mapping of Ignalina NPP area at a scale 1:50 000 in topographical sheets N-35-5-G-v,g, N-35-6-V-v,g, N-35-17-B, N-35-18-A, N-35-17-G-a,b, N-35-18-V-a,b (Report of Drūkšiai object)]. 1995. *LGT Archive*, 4384. Vilnius.