since 1961

Baltica

http://www.geo.lt/geo/index.php?id=710

BALTICA Volume 25 Number 2 December 2012 : 91–98
doi:10.5200/baltica.2012.25.09

The Quaternary aquifer system flow model by chemical and tritium isotope data: case of south-east Lithuania

Anicetas Štuopis, Vytautas Juodkazis, Robert Mokrik

Štuopis A., Juodkazis V., Mokrik R., 2012. The Quaternary aquifer system flow model by chemical and tritium isotope data: case of south-east Lithuania. *Baltica, 25 (2), 91-98.* Vilnius. ISSN 0067-3064.

Manuscript submitted 21 March 2012 / Accepted 30 October 2012 / Published online 10 December 2012

Abstract The hydrogeological schematisation of the multi-layered stratigraphical sequence and the results of groundwater flow modelling by MODFLOW code for the Quaternary aquifer system of the south-eastern part of Lithuania have been discussed in the paper. The regional groundwater steady-state flow model has been calibrated applying hydrochemical and isotope data. A tritium isotope data set for groundwater in upland, transit and lowland sites has been used to identify the flow model for water residence time.

Keywords • *Groundwater flow model • Tritium isotope • Hydrogeological schematisation • Lithuania*

Anicetas Štuopis, Vytautas Juodkazis, Robert Mokrik (robert.mokrik@gf.vu.lt), Vilnius University, K. M. Čiurlionio g. 21/27, LT-03101 Vilnius, Lithuania.

INTRODUCTION

The Quaternary cover in the 20,880 km^2 area of south-east Lithuania is formed by at least three mean continental glacier stages and several substages when ice sheet advances and retreats took place. This results in the appearance of a multi-layered aquifer system.

Two main subjects are discussed in the paper: (1) the principles of schematisation of the Quaternary deposits with respect to the distribution of aquifers and regional groundwater flow rate, and (2) the calibration of steady-state groundwater flow model applying hydrochemical, borehole hydraulic test and tritium isotope data. The numerical representation of Quaternary aquifer system is undertaken applying the MODFLOW-2005 code (Harbough 2005), which uses the finite difference method to solve the partial differential equations to aquifer and aquitard units. The licensed software of U.S. Environmental Simulations Inc. company Groundwater Vistas Enterprise v5 (Rumbaugh, J. O., Rumbaugh D. B. 2007) has been used for the management of the mentioned software, as well as for the graphic depiction and analysis of the results.

Hydrochemical and isotopic techniques provide additional information for building up the conceptual regional groundwater flow model and its calibration. All the analysed chemical data of groundwater are incorporated into the aqueous chemistry database allowing for the analysis of groundwater types. The volumetric activity of ^3H in water samples is determined by different counters and more recently by the LSA Tri-Carb 3170TR/SL at the Radioisotope Research Laboratory of the Institute of Geology and Geography in Vilnius. The beta decay counting of ^3H is run for a scintillation cocktail with 12 ml of PtiPhase „TriSafe“ and 8 ml of water electrolytically enriched with ^3H. The main performance parameters of the spectrometric system for ^3H with 20 ml plastic vials are as follows: background count rate being 1.0±0.08 CPM, counting efficiency 22.0±0.4 %. The detection limit for ^3H is 2 TU.

HYDROGEOLOGICAL SEQUENCE AND PRINCIPLES OF SCHEMATISATION

Data obtained by mapping and research on geological structure and groundwater water bodies is used for distinction and spatial occurrence representation of layers in the simulation model, as lithology of their profile is well described and profiles are reliably divided according to stratigraphic subdivision. Meanwhile the most reliable hydraulic parameters are obtained from the exploration boreholes of aquifers, where hydraulic tests have been carried out and water level was measured in the pumping and observation wells. The greater part of hydraulic parameters used in modelling are obtained in water supply wells making the majority of all drilled wells in the studied territory (Fig. 1).

The Quaternary cover is notable for variable glacial and interglacial/interstadial strata determined by peculiarities of their formation, which has been regarded schematising geological-hydrogeological conditions: glacio-aqueous deposits (mostly sand and loamy sand, gravel, and pebble) were formed by ice thawing flows

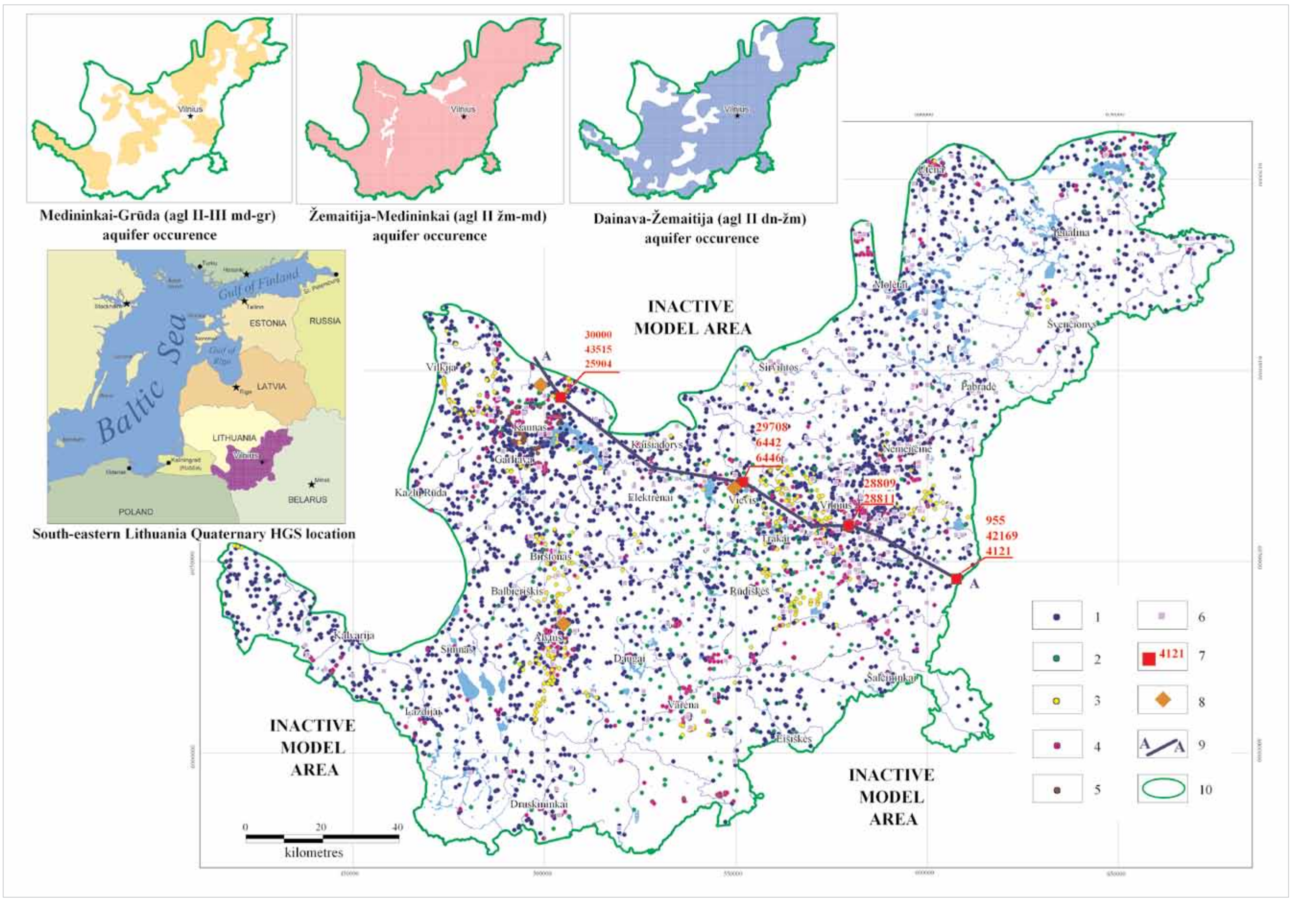

Fig. 1 Location map: 1 – water extraction boreholes; 2 – mapping and structural boreholes; 3 – exploration boreholes; 4 – groundwater monitoring boreholes; 5 –engineering-geological test boreholes; 6 – waterworks; 7 – site of groundwater sampling for isotopic test and the number of sampling borehole; 8 – site of borehole (Fig. 2); 9 – line of geological cross section (Fig. 3); 10 – boundary of Quaternary aquifer system. Compiled by A. Štuopis, 2012.

of different strength, forms of relief and ice bodies thicknesses; during the glacier motion and degradation complex processes of earlier formed deposits the erosion and matter removal took place, thus deepened valleys and local incisions, which constitute direct hydraulic interference between separated confined aquifers, were formed; permeable layers are separated irregularity with semi-permeable beds. Lenses and thin sandy interlayers cannot be considered as independent aquifers, but will be integrated into mean aquifer units during schematisation on the model.

There are five aquifers distinguished: Dzūkija-Dainava (=Elsterian interglacial aglIIdz-dn), Dainava-Žemaitija (=Holsteinian interglacial aglIIdn-žm), Žemaitija-Medininkai (=Saalian-Warthian interstadial aglIIžm-md), Medininkai-Grūda (=Eemian-Middle Weichselian interglacial/interstadial aglII-IIImd-gr), Grūda-Baltija (=Upper Weichselian interstadial aglII-Igr-bl). However the spread and practical significance of these aquifers are not equal. The Dzūkija-Dainava aquifer is sporadically spread and related only with palaeo-incisions. The Grūda-Baltija and Dzūkija-Dainava aquifers are also spread locally, and because their hydraulic interferences are obviously close to neighboring aquifers, they can be directly connected to the Medininkai-Grūda and Dainava-Žemaitija aquifers. Meanwhile other interglacial/interstadial aquifers mentioned above are spread rather widely but they are significant, therefore they are distinguished into separate layers on the flow model.

Hydrogeochemical criteria are applied to prove similarity of hydrochemical facies in aquifers. For this purpose groundwater hydrochemical facies are systemised according to the regional hydrochemical classification of the Baltic artesian basin, which is based on the expression of the groundwater metamorphic degree (GMD) coefficient $(Na^{+} + Cl^{-})/HCO_3^{-}$. This ion ratio reflects the alteration of the groundwater chemical composition from the recharge area to the discharge area and the latter groundwater can be divided into types (Mokrik 2003; Mokrik *et al.* 2009).

Chemical groundwater composition of the Žemaitija-Medininkai and Dainava-Žemaitija aquifers according to GMD coincide with of approximately 42 % of the model area. Meanwhile the chemical groundwater composition of the Medininkai-Grūda and Žemaitija-Medininkai aquifers according to GMD coincide with approximately 21 % of the area, and all three distinguished interglacial/interstadial aquifers coincide with only 7 % of the model area. Thus, the results obtained after the analysis of groundwater chemical composition show that the aquifers described in the largest model area (Žemaitija-Medininkai and Dainava-Žemaitija) are still rather well isolated from each other, and their distinction as separate layers in the flow model is reasonably motivated according to the criteria of hydrochemical facies.

Hydrodynamic criteria were also applied for aquifer systems to evaluate distribution of piezometric levels and flow directions as well as model balance. If the piezometric level of interglacial/interstadial aquifers is close to each other, i.e. it does not differ more than 1.0–1.5 m, it shows that aquifers are connected from the point of view of hydraulic interference. The hydrodynamic criteria also enable to reveal that in the major part of the studied model area, the aquifers are enough isolated.

Thus, all three aquifers according to both of the abovementioned criteria are close to each other located in an area of only 200 km^2, which constitutes only 1 % of the entire modelled territory. Therefore, with regard to the obtained results, it can be assumed that the described aquifers in the major part of the flow model can be schematised into separated layers.

For the conjoined aquifers the hydraulic conductivity has been calculated using the equation (Sepulveda, Kuniansky 2010):

$$k = \frac{k_1 m_1 + k_2 m_2 + \cdots + k_n m_n}{m_1 + m_2 + \cdots + m_n}, \quad (1)$$

where m_1, m_2, m_n refers to the thickness of the layers; k_1, k_2, k_n is the hydraulic conductivity of layers. For the connection in the model of the semi-permeable layers or aquitards hydraulic conductivity were calculated as follows:

$$k = \frac{m_1 + m_2 + \cdots + m_n}{\frac{m_1}{k_1} + \frac{m_2}{k_2} + \cdots + \frac{m_n}{k_n}}. \quad (2)$$

THE CONCEPTUALISATION OF GROUNDWATER FLOW MODEL

Regarding the occurrence and spreading conditions of the described interglacial/interstadial aquifers, three typical schemes with three, two and one aquifer correspondingly has been revealed (Fig. 2). It should be noted that all layers distinguished in the model have to be uninterrupted in the model grid net. Therefore in order to satisfy the mentioned condition of the MODFLOW code a fictive thickness of a layer of 0.05 m thick is adopted in places where the layers not exist.

Thus creating a conceptualisation of the regional flow in the Quaternary aquifer system, regarding structural particularities of multi-layered system discussed above, 11 layers are distinguished in the model (Fig. 3). A technique created at the Riga Technical University's Environmental Modelling Centre has been used for unconfined aquifer recharge simulation. Its essence is that the landscape elevation serves as boundary condition H=const. The rate of infiltration flow in each active model grid is obtained by selecting the size of conductivity in the unsaturated zone (2nd layer) between landscape elevation and the unconfined aquifer level (Spalvins 2000; Spalvins *et al.* 2004).

The third layer in the model is the unconfined aquifer that depends on lithology in the upper part of the geological profile, and its thicknesses is schematised according to the Geological Map of Quaternary Deposits at a scale of 1:200 000 (Guobytė 1998). Where the unconfined aquifer is quite thick (20–50 m), the thicknesses of the unsaturated zone and unconfined groundwater table are given according to the borehole data.

The Medininkai-Grūda aquifer, being the fifth layer in the model, occurs in the area of 8,570 km^2 or 52 % of the described territory (see Fig. 1). The height of the top of the aquifer follows the trend of contemporary relief, i.e. it rises up to 180–265 m a.s.l. on the uplands and it goes down to 20 m a.s.l. and below in lowlands surround Kaunas city. The thickness of this layer varies from 10–20 to 40 m.

The Žemaitija-Medininkai aquifer (7th layer) is spread in the area of 15 600 km^2 and covers 95 % of the studied territory (see Fig. 1). This aquifer is absent in the valleys of the Nemunas and Neris rivers. The highest position of the top of the layer is in the areas of uplands, i.e. 140–200 m a.s.l. Meanwhile in the Kaunas district, in the plateau of the Middle Nemunas it descends down to 20 m below sea level or even farther down. This aquifer is found to be the thickest in the uplands of Švenčionys and Ašmena, and in the regions surrounding Kaunas (40 m and more). The thickness of the layer in the remaining part of the modeled territory varies from 1 to 30 m.

The Dainava-Žemaitija aquifer (9th layer) is spread out in the area of 12 360 km^2 or 75 % of all the territory (see Fig. 1). This layer is not distinguished in the Middle Nemunas plateau neither in the local areas of the uplands of Dzūkija, Aukštaičiai, and Sūduva. The top of the aquifer rises up to 120–140 m a.s.l. in the uplands. Meanwhile in the Middle Nemunas plateau, the top of the aquifer descends down to 20 m below sea level. In the major part of the area, the absolute altitude of the top varies from 50 to 80 m above sea level. The thickness of the aquifer varies from 1 to 45 m, and thickness of 10–20 m prevails, but it can reach up to 150 m in palaeoincisions. All the mentioned aquifers are separated by semi-permeable Quaternary derivatives (2nd, 4th, 6th, 8th, 10th layers of the model). The 11th layer of the model consists of one integrated layer of the pre-Quaternary aquifers (see Fig. 3).

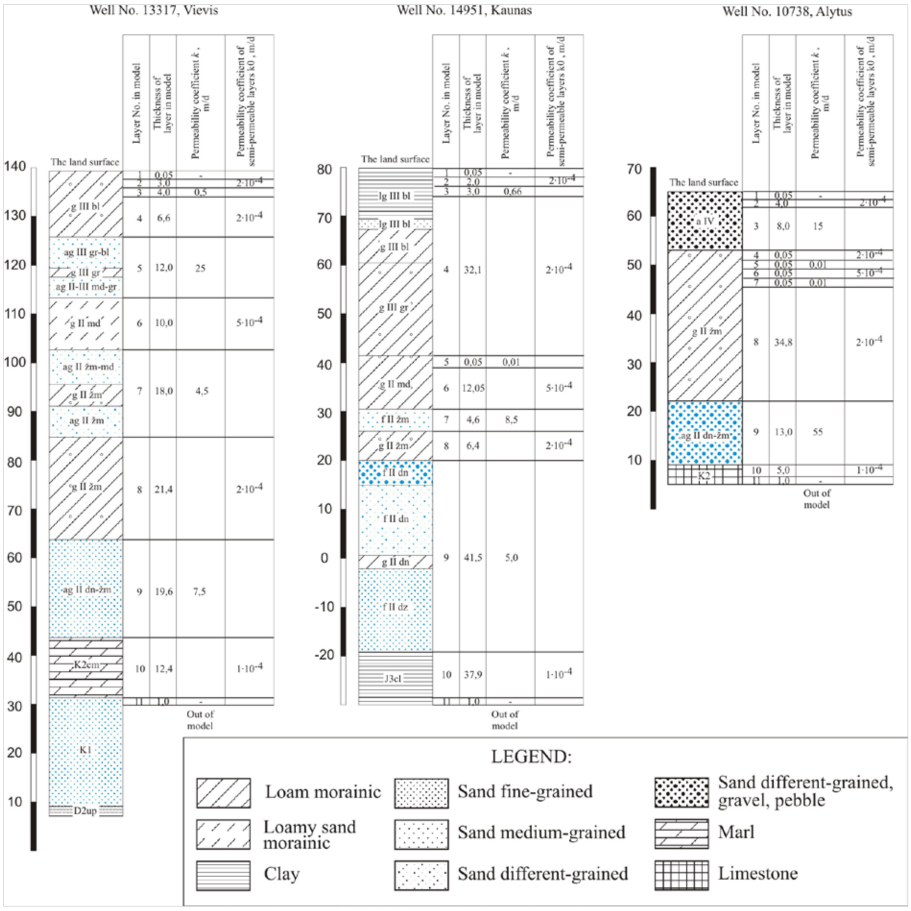

Fig. 2 Borehole logs in different geological environment: case of Vievis, Kaunas, and Alytus (sites are shown on Fig. 1). Compiled by A. Štuopis and R. Mokrik, 2012.

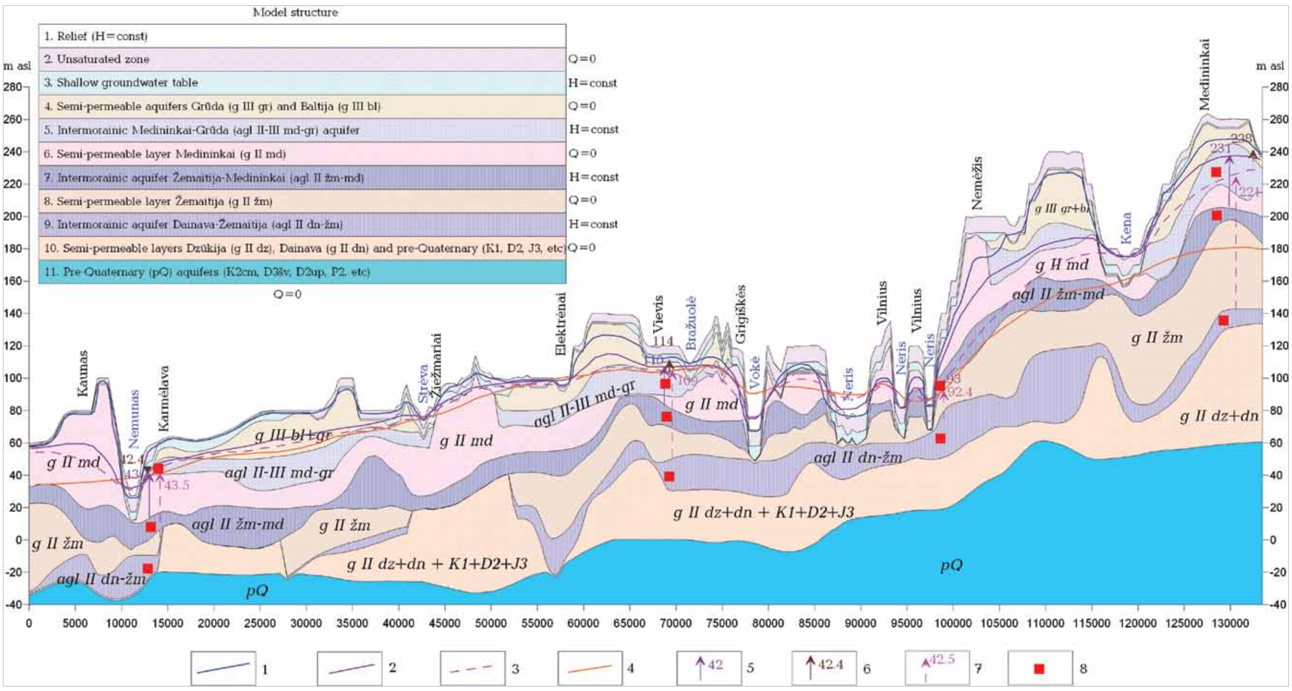

Fig. 3 Geological cross section and model structure: 1 – unconfined groundwater table; 2 – piezometric level of Žemaitija-Medininkai aquifer; 3 – piezometric level of Dainava-Žemaitija aquifer; 4 – piezometric level of pre-Quaternary aquifers; 5 – head of Medininkai-Žemaitija aquifer in a borehole, m a.s.l.; 6 – head of Žemaitija-Medininkai aquifer in borehole, m a.s.l.; 7 – head of Dainava-Žemaitija aquifer in borehole, m a.s.l.; 8 – point of groundwater isotopic test. Compiled by A. Štuopis, 2012.

In the model, the boundary condition Q=0 is given at the northern and western lateral boundaries of aquifers, coinciding with boundaries of the layer's crops. The boundary condition of H=const is set for the territories of Lithuania's neighbours (Belarus, Poland, Russia). Boundary condition Q=0 is realized for the boundaries of the model of semi-permeable layers. As already mentioned above, land surface relief is the upper boundary of the model (H=const). Inner boundary conditions of the model are bodies of surface water (rivers, lakes), i.e. H=const. The surface water bodies are put in the third layer of the model, i.e. in the unconfined aquifer. In total, 77 rivers and 268 lakes are imposed into the model.

The finite difference approximation plane step of the model is 500 metres. Each of eleven model grid planes contains 412×581=244,601 cells of the 500m×500m size. The model area includes its active and passive parts (see Fig. 1). The full 3D model grid contains 11×244,601=2,690,611 cells. The active model volume contains 1,152,681 cells.

STEADY-STATE GROUNDWATER FLOW MODEL CALIBRATION

The ability to model groundwater regional flow accurately is dependent upon the availability of transmissivity, boundary conditions and recharge for the given aquifer system. The groundwater flows from highlands to lowlands, with recharge occurring mostly in the eastern part of the model, and is directed to the west and down through the semi-permeable layers, ensuring infiltration recharge of aquifers (Fig. 3). The discharge flow in deep river valleys and lowlands goes up towards the surface with seepage into the rivers and unconfined aquifers. It can be obviously seen that for majority sites of regional profile the hydraulic gradient of the lateral flow is significant as the depth of aquifers sharply increases westwards from the upland.

Transmissivity (T) values range in the Medininkai-Grūda aquifer (aglII-IIImd-gr) from 150 to 500 m^2/d, in Žemaitija-Medininkai aquifer (aglIIžm-md) 190–500 m^2/d and in the Dainava-Žemaitija aquifer (aglIIdn-žm) 250–500 m^2/d correspondingly. In water supply wells, where only short-term pumping was carried out, the transmissivity is calculated using the following formula:

$$T = \frac{0{,}366 \cdot Q \cdot \lg \frac{R}{r_0}}{S}, \quad (3)$$

where T is the aquifer transmissivity, m^2/d; Q is the pumping rate of the borehole, m^3/d; R is the radius of borehole influence, m; r_0 is the radius of the borehole, m; and S is the drawdown, m.

In order to systemize the retrospective well hydraulic test data by specific capacities, when actual values of some pumping parameters are absent, the following empirical equation is used:

$$T = 15 \cdot q^{0.87}, \quad (4)$$

where $q = Q/S$ – the specific capacity of the borehole, m^2/d.

The steady-state flow model calibration involved the estimation of inflow and outflow rates bringing out distribution of optimal transmissivity and leakance factor values on the grids of the model. During the model calibration, the unconfined aquifer table and potentiometric surfaces of all the interglacial aquifers have been restored to no pumping regime, i.e. pre-exploitation of the waterworks' regime. During model calibration filtration properties of aquifers and separating semi-permeable layers have been adjusted. Filtration properties of the aquifers are rather variable (Table 1). Prevailing values of hydraulic conductivities k and transmissivities T respectively range from 5 to 10 m/d and from 50 to 200 m^2/d. The greatest values of the transmissivity T coefficient are usually observed at the places of exploited large waterworks and directly related to the efficient thickness of aquifers. Effective porosity has been assumed for the entire region based on geological features and these values were assigned to the model. Calibrated values of transmissivity of aquifers as well as hydraulic conductivities of semi-permeable layers yield the best possible coincidence between model heads and actual heads in the boreholes. More than 800 monitoring boreholes were used as the calibration targets for aquifers. Satisfactory match up has been achieved between the observed and modeled heads. The standard deviation is within 2.49–3.08 meters and the relative deviation obtained as the "standard deviation/observed range" does not exceed 0.018 (1.8 %).

The hydraulic conductivity (k_0) of morainic loam, often with sand and gravel insertions (lenses and interlayers), varies from 10^{-5} to 10^{-2}, tight clay respectively from 10^{-7} to 10^{-6} m/d and depends on the sediments type. The hydraulic conductivity (k_0) of morainic loam, as well as other semi-permeable rocks is from 10 to 100 times higher in river valleys or palaeoincisions. This phenomenon probably is caused by two reasons: first, poorly consolidated and sorted clastic facies prevail in the palaeovalleys, and second, river valleys and the old buried palaeovalleys often lie close to the crumbles and

Table 1 Adjusted hydraulic parameters used in the model. Compiled by A. Štuopis and R. Mokrik, 2012.

Aquifer	Transmissivity T, m^2/d	Hydraulic conductivity k, m/d	Effective porosity
Unconfined aquifer	1–960	0.2–40	0.1–0.3
ag II-III md-gr	20–400	2–45	0.15–0.3
ag II žm-md	20–5,000	0.5–143	0.1–0.3
ag II dn-žm	20–1,200	1.7–40	0.15–0.3

fractured bedrock near the tectonic zones. In such cases the rock layers become more permeable. According to the data of model calibration, hydraulic conductivities values of semi-permeable layers, which separate aquifers, on the model varies from $5\times10^{-7}$to 0.15 m/d and leakance coefficient k_0/m_0 values vary from 1×10^{-6} to 2×10^{-3} 1/d (Table 2). These semi-permeable layers in river valleys, which are the main areas of outflow in the basin, have much better hydraulic properties compared to those in the surrounding area, which can

Table 2 Adjusted leakance parameters used in the model. Compiled by A. Štuopis and R. Mokrik, 2012.

Semi-permeable layer	Leakance coefficient k_0/m_0, 1/d	Hydraulic conductivity k_0, m/d	Effective porosity
Unsaturated zone	1×10^{-6} – 1×10^{-3}	4×10^{-6} – 8×10^{-3}	0.006–0.009
g III bl+gr	1×10^{-6} – 1×10^{-3}	5×10^{-7} – 0.06	0.005–0.01
g II md	2×10^{-6} – 1×10^{-3}	5×10^{-7} – 0.09	0.005–0.01
g II žm	2×10^{-6} – 1×10^{-3}	2×10^{-7} – 0.15	0.005–0.01
g II dn+dz and pre-Quaternary layers	1×10^{-6} – 1×10^{-3}	3×10^{-6} – 0.02	0.006–0.01

be explained by the increased grain sizes of sediments.

In all the studied area, intense water exchange via confining units between unconfined aquifers and surface water bodies as well as between unconfined aquifer and confined aquifers take place (Fig. 4). Total infiltration recharge of the unconfined aquifer in the described territory, according to the model results, is 8.94 million m^3/d (162.51 mm per year), and input of infiltration recharge is 6.81 million m^3 per day (123.74 mm per year or 81 %). Infiltration recharge values adjusted during model verification conform well to the average and maximal infiltration recharge values, set by monitoring hydrodynamic investigation methods (Sakalauskienė 1973). According to the model data, the major part of unconfined groundwater outflows to surface water bodies (65.7 %); the remaining part (27.5 %) discharge through the confined interglacial/interstadial aquifers and outflows across the lateral boundaries (6.8 %) (Table 3).

The total groundwater flow rate of the confined aquifers is 2,920 thousands m^3/d or 53.04 mm per year (the modulus is 1.68 l/s in one km^2). Most of them (84 %) are formed by recharge from an unconfined aquifer – 2,460 thousands of m^3/d (44.63 mm per year); the residual part is formed by lateral groundwater inflow and from the pre-Quaternary aquifers. The majority of groundwater resources of confined aquifers are discharged back into unconfined aquifer and surface water bodies, i.e. – 68 %. Approximately 18 % of the groundwater from confined aquifers outflow via lateral boundaries and pre-Quaternary aquifers (Fig. 4).

Table 3 Modelled groundwater balance of the Quaternary aquifer system. Compiled by A. Štuopis, 2012.

Inflow			Outflow		
Source	Quantity		Source	Quantity	
	In thousands m^3/d	mm/year		In thousands m^3/d	mm/year
Unconfined aquifer					
Infiltration recharge	6,810	123.74	Outflow in slopes of surface water bodies	408	7.41
Inflow from surface water bodies	-	-	Outflow to surface water bodies	5,470	99.43
Inflow from intermorainic confined layers	1,670	30.35	Outflow to intermorainic confined aquifers	2,460	44.63
Lateral inflow	463	8.42	Lateral aquifer	607	11.04
Total:	8,940	162.51	Total:	8,940	162.51
Interglacial/interstadial confined aquifers					
Inflow from unconfined aquifer	2,460	44.63	Outflow to unconfined aquifer	1,670	30.35
Inflow from pre-Quaternary aquifers	108	1.97	Outflow to pre-Quaternary aquifers	500	9.09
Lateral inflow	354	6.43	Lateral outflow	748	13.59
Total:	2,920	53.04	Total:	2,920	53.04
Pre-Quaternary aquifers					
Inflow from Quaternary confined aquifers	500	9.09	Outflow to Quaternary confined aquifers	108	1.97
Lateral inflow	106	1.93	Lateral outflow	498	9.05
Total:	606	11.02	Total:	606	11.02

The most intense outflow modules are in the basins of the rivers Neris, Žeimena, and Merkys, where its value is more than 4 l/s in km^2. Meanwhile in the Šešupė river basin, where an unconfined aquifer occurs mostly in morainic loam mostly, the value of groundwater outflow is less than 1.4 l/s in km^2. The values obtained in the model for groundwater outflow coincide rather well with factual modulus values set dividing river hydrographical nets (Gailiušis *et al.* 2001).

APPLICATION OF ISOTOPE DATA FOR MODEL CALIBRATION

To verify this first ever compiled regional mathematical model, the data set on the groundwater residence time evaluation by mathematical modelling and according to groundwater tritium isotopes have been

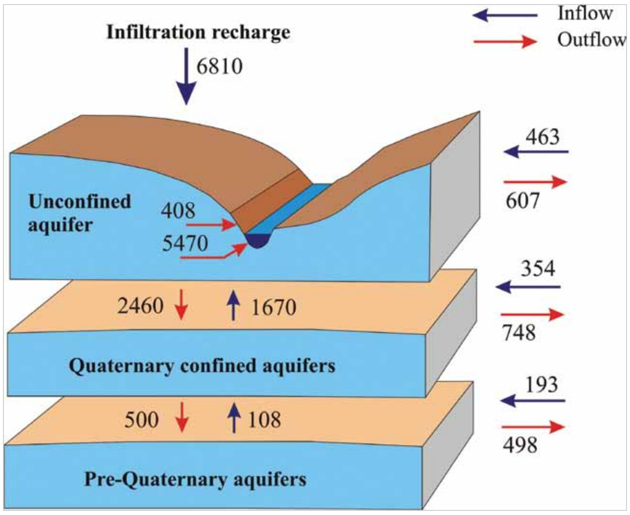

Fig. 4 The water balance scheme of the steady-state flow model of the Quaternary aquifer system (thousand m^3/d). Compiled by A. Štuopis, 2012.

used. The results obtained by these two methods can be compared with each other. Groundwater samples to determine volume activity of tritium (^3H) have been analyzed for enriched ^3H from 11 wells at four places on the cross-section, i.e. Medininkai, Vilnius, Vievis, and Karmėlava. The samples are chosen to represent different groundwater flow zones including recharge, transit and discharge areas, thus the groundwater age would be determined in all three intermorainic aquifers distinguished in mathematical model (see Fig. 1). The ^3H data and age were corrected and calculated using the ^3H decay equation with the half-life $t_{1/2}$ of 12.43 years (Clark, Fritz 1997). The groundwater age for these places is evaluated according to the data from the mathematical model as well. The measured and interpretative data of tritium and modelled ages are presented (Table 4).

In the calibrated groundwater flow model setting water flow velocity in separate blocks, the particular amount of elementary particle ***p*** is given and their migration in 3D cell of finite differences is modelled according to the flow in space and time by the MODPATH particle tracking post-processing package code. Generally such migration occurred according to the *x* axis as described using the equation (Pollock 1994):

$$x_p(t_2) = x_1 + \left(\frac{1}{A_x}\right)\left\{v_{x_p}(t_1)\exp(A_x \Delta t) - v_{x_1}\right\}, \quad (5)$$

where $A_x = \frac{v_{x_2} - v_{x_1}}{\Delta x}$ is the constant that corresponds to the component of the velocity gradient within the cell; x_p – the location of the particle; v_{xp} – the velocity component of the particle; t_1 and t_2 – the initial and future times of the particle correspondingly. The same procedure is valid for other model axes.

The isotope investigation done in the given cross section shows that the volume activity of tritium (^3H) in groundwater has changed from 2.3 to 10.2 TU with values below 2 TU observed only in two samples, where the age cannot be determined (Table 4). The majority of groundwater residence time results obtained according to the volume activity of tritium (^3H) is up to 10–56 years. Two above samples taken from the discharge area of Žemaitija-Dainava aquifer have shown the volume activity of tritium is below 2 TU, where the groundwater age is longer than 60 years, thus according to the model it is equated to that for nearby wells Nos 6446 and 25904 respectively to 183–215 years. High tritium values (4.4–10.2 TU) of groundwater indicate a modern recharge showing that the water is of recent meteoric origin. The submodern water is recharged prior to 1952. Transition from the modern to submodern tritiated groundwater revealed in the Nemunas River Lowland (Karmėlava) and Neris river valley (Vievis), i.e. on the discharge area of the aquifers laying beneath it (Fig. 3, Table 4).

The obtained modelling results for the investigated sites of multi-layered Quaternary strata show that groundwater residence time varies from 8 to 215 years, i.e. these results also allow to attribute the water to two types: modern and submodern tritiated meteoric water (from several tenths to several hundred years). The trend of the typical vertical and lateral downgradients increasing by residence time from upper to lower layered aquifers and from the recharge area to the discharge area are also respectively detected according to the flow

Table 4 Groundwater residence time according to the data of groundwater flow model velocities and volume activities of tritium (^3H) isotope. Compiled by A. Štuopis, V. Juodkazis and R. Mokrik, 2012.

Well No.	Well location	^3H activity, TU	Groundwater residence time according to tritium, years	Groundwater residence time set by mathematical modeling, years
Medininkai-Grūda (agl II-III md-gr) aquifer				
955	Medininkai	7.5	10–13	19
29708	Vievis	5.5	23–24	28
30000	Karmėlava	7.3	10–15	26/18*
Žemaitija-Medininkai (agl II žm-md) aquifer				
42169	Medininkai	8.5	27	44/35*
28809	Vilnius	10.2	30	8/25*
6442	Vievis	2.6	55	65
43515	Karmėlava	2.3	56	57
Dainava-Žemaitija (agl II dn-žm) aquifer				
4121	Medininkai	7.5	10–13	55/20*
28811	Vilnius	4.4	25	46/30*
6446	Vievis	<2	>60 (183)	183
25904	Karmėlava	<2	>60 (215)	215

Note. In brackets – tritium residence time is corrected by modelling data; *– groundwater residence time according to tritium data correction on the model.

model and tritium data. It shows that a recharge to the under layered aquifers via aquitards and the discharge from the deepest part of lower layered pre-Quaternary aquifers took place.

Tritium data collected in the surroundings areas of the wells Nos 30000, 42169, 28809, 4121 and 28811 have been used to verify the flow model on the vicinity of the cross section grids close to the Medininkai site according to tritium residence time and *vice versa* – tritium age, which was fixed < 2TU (^{3}H) content in groundwater, can be corrected by modelling data. It shows that volume activities of tritium (^{3}H) may be applied directly during for flow model verification and has been successfully used for the schematisation of the Quaternary multi-layered strata.

CONCLUSIONS

The first regional steady-state flow model of the Quaternary aquifer system is compiled in the south-eastern part of Lithuania. Taking into account a heterogeneity of the multi-layered system, eleven hydro-stratigraphic units, including Medininkai-Grūda, Žemaitija-Medininkai and Dainava-Žemaitija interglacial/intersatadial aquifers, have been taken to this model. Such a subdivision of the system into separate modelled aquifers is based on the hydrodynamic, hydrochemical and tritium isotope data.

The conceptual model of the Quaternary aquifer system, developed using numerical code MODFLOW, allowed (1) to approach the schematisation principles of the multilayered Quaternary deposits with respect to its aquifer system strata, and (2) to calibrate mathematical model with respect to vertical and horizontal groundwater flows also distribution of their velocities. The adequacy of water balance is supported by verifying of the created mathematical model of tritium dating.

Hydrochemistry and isotopic techniques, as an additional source for build up the given model have been used in order to prove similarity of hydrochemical facies composition in aquifers. Data of groundwater chemical composition show up that described intermorainic layers in the greater part of the modelled area are rather well isolated from each other. Therefore, their distinction as separate modelled layers in mathematical model is motivated by these hydrochemical facies criteria.

The varying data of the groundwater tritium composition that was estimated along the cross-section from the research area to discharge area have been used into the simulated flow model. These data of groundwater residence time according to volume activity of tritium (^{3}H) let significantly improve the schematisation of the regional groundwater flow model. The modelling validation by tritium (^{3}H) isotope values on the vertical profile from the recharge area (Vilnius) to discharge area (Kaunas) finally showed a good agreement between the measured and modelled velocities or residence times.

Acknowledgements

The authors are grateful to reviewers Professor Aivars Spalvins (Rīga) and Dr. Marius Gregorauskas (Vilnius) for their critical comments that allowed to improve the quality of the manuscript. Professor Jonas Mažeika (Vilnius) is thanked for help in the laboratory for the tritium analyses.

References

Clark, I. D., Fritz, P., 1997. *Environmental isotopes in hydrogeology.* Lewis, Boca Raton, FL, 328 pp.

Gailiušis, B., Jablonskis, J., Kovalenkovienė, M., 2001. *Lithuanian rivers. Hidrography and runoff.* Kaunas, Lithuanian Energy Institute, 792 pp. [In Lithuanian].

Guobytė, R., 1999. *Quaternary geological map of Lithuania. Geochemical atlas of Lithuania*. Vilnius, Geological Survey of Lithuania and Institute of Geology, 91 pp. [In Lithuanian].

Harbaugh, A. W., 2005. *MODFLOW-*2005*, U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process. Chapter 16 of Book 6. Modeling techniques, Section A. Ground Water.* U. S. Geological Survey, Reston, Virginia.

Mokrik, R., 2003. *The palaeohydrogeology of the Baltic basin*. *Neoproterozoic and Phanerozoic.* VUL, Vilnius, 332 pp. [In Lithuanian].

Mokrik, R., Mažeika, J., Baublytė, A., Martma, T., 2009. The groundwater age in the Middle-Upper Devonian aquifer system, Lithuania. *Hydrogeology Journal 17,* 871–889.

Pollock, D. W., 1994. *User's Guide for MODPATH/ MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, U. S. Geological Survey finite-difference groundwater flow model.* U. S. Geological Survey, Open File Report 94–464, Reston, Virginia.

Rumbaugh, J. O., Rumbaugh D. B., 2007. *Groundwater Vistas version* 5. *Guide to Using.* Environmental Simulations, Inc., 381 pp.

Sakalauskienė, D., 1973. *Zakonomernosti gidrodinamiceskogo rezima gruntovych vod Litovskoi SSR i ocenka ich estestvennych resursov* [Peculiarities of the groundwater hydrodynamic regime and assessment their flow rates, Lithuania]. Thesis of Ph. D., Vilnius, 24 pp. [In Russian].

Sepulveda, N., Kuniansky, E. L., 2010. Effect of model layer simplification using composite hydraulic properties. *Hydrogeology Journal 18 (2),* 405–416.

Spalvins, A., 2000. Landscape elevation maps as reliable boundary condition for hydrogeological models. *Scientific Proceedings of Riga Technical University in series "Computer Science",* Vol. 4, 47–50.

Spalvins, A., Slangens, J., Janbickis, R., Lace, I., 2004. Two helpful ideas for users of MODFLOW. *Scientific Proceedings of Riga Technical University in series "Computer Science",* Vol. 21, 172–178.