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CREATING OF REGIONAL HYDROGEOLOGICAL MODEL FOR SOUTH-EAST OF LITHUANIA

REĢIONĀLĀ HIDROĢEOLOĢISKĀ MODEĻA IZVEIDE LIETUVAS DIENVIDAUSTRUMU DAĻAI

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The regional hydrogeological model (HM) has been developed for the Quaternary groundwater system located in the South- East of Lithuania. This groundwater body covers one third of Lithuania. The rectangular HM area has the size 290 km × 210 km. Six local river basins comprise the active HM area of irregular shape. The model area, exterior to the active one, does not take part in simulation. Innovative methods were used to create HM: the ground surface elevation map as the piezometric boundary condition regulated the infiltration flow on the HM top surface; the aeration zone was treated as a formal aquitard; during the first stage of HM building, no real geometry of geological layers was used. Due to these innovations, very complex regional HM was built at the short time, in comparison with the case when the classic methods were applied.

Introduction

Lithuania possesses rich resources of groundwater. However, not everywhere, groundwater quality meets standards for drinking water, due its natural and anthropological contamination. To fulfill the water directives of the European Commission (98/83 EC, 2000/50 EC), Lithuania has prepared the program (2007 - 2025) focused on improving management of groundwater resources and on supplying the country population with drinking water of high quality. The program includes the task to evaluate groundwater resources by using modern methods of mathematical modeling for processing accumulated hydrogeological data.

In Lithuania, to facilitate the task of modeling and to distribute it between different contractors, separate HM are under development for Quaternary and pre-Quaternary type groundwater systems. The river basin method is applied, to split the Quaternary groundwater body into the separate ones suitable for diverse HM.

For the first time, regional HM has been developed for the Quaternary system located in the South-East of Lithuania. This groundwater body covers one third (20880 km^2) of the country (see Fig. 1). The rectangular HM area has the size 290 km × 210 km = 60900 km^2. Six river basins (Neris, Merkys, Zeimena, Nemunas, Sesupe, Sventoji) comprise the active HM area of the irregular shape (see Fig. 2). The model area, exterior to the active one (40020 km^2) does not take part in simulation.

The Groundwater Vistas (version 5) system (GV) [1] was used for HM creating. The MapInfo Professional system [2] and the program GDI [3] served for preparing digital hydrogeological maps.

Fig. 1. Model location

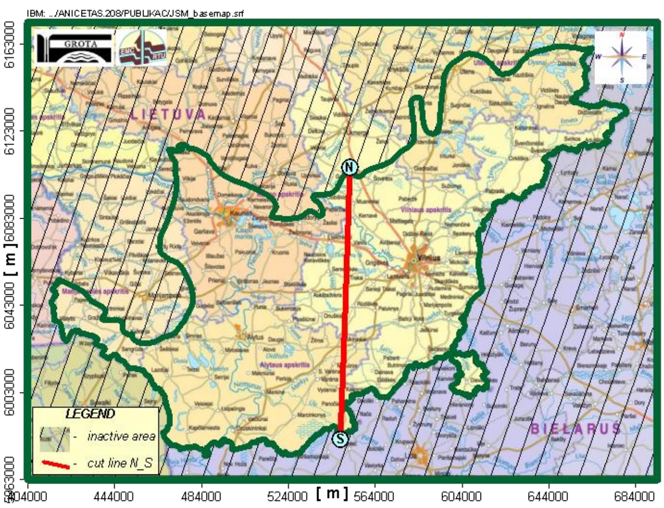

Fig. 2. Model area (290 km × 210 km, h = 0.5 km)

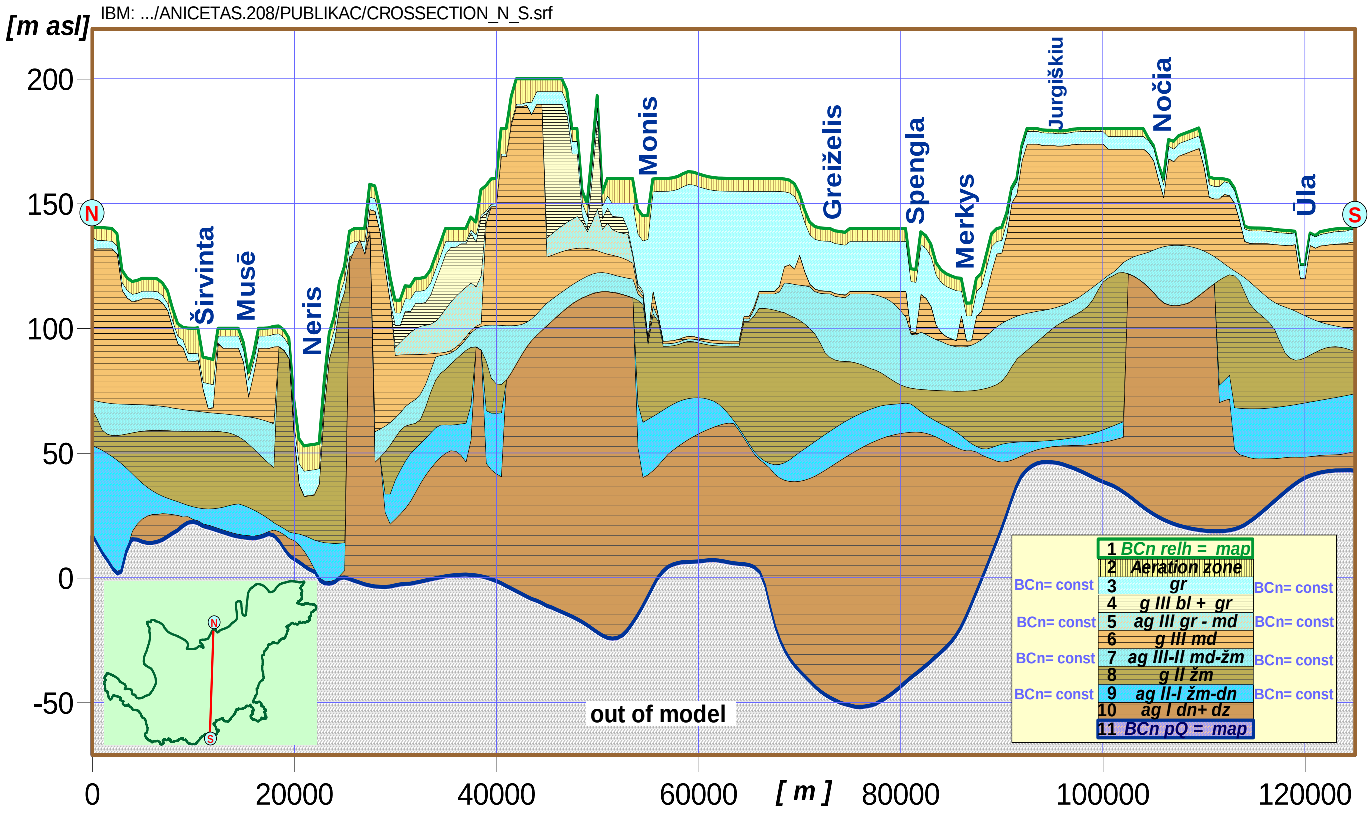

Fig. 3. Geological cross section NS

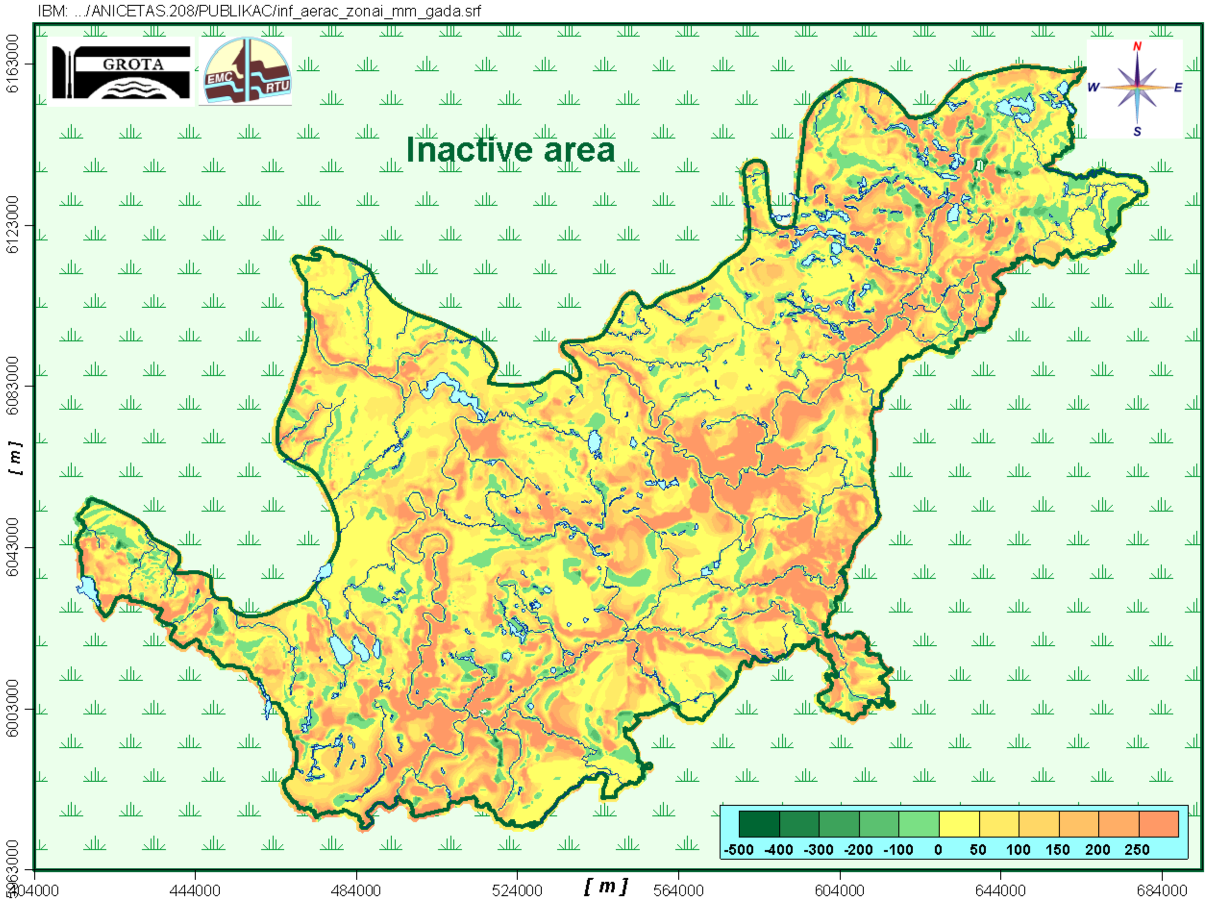

Fig. 4. Infiltration flow [mm/year] of aeration zone

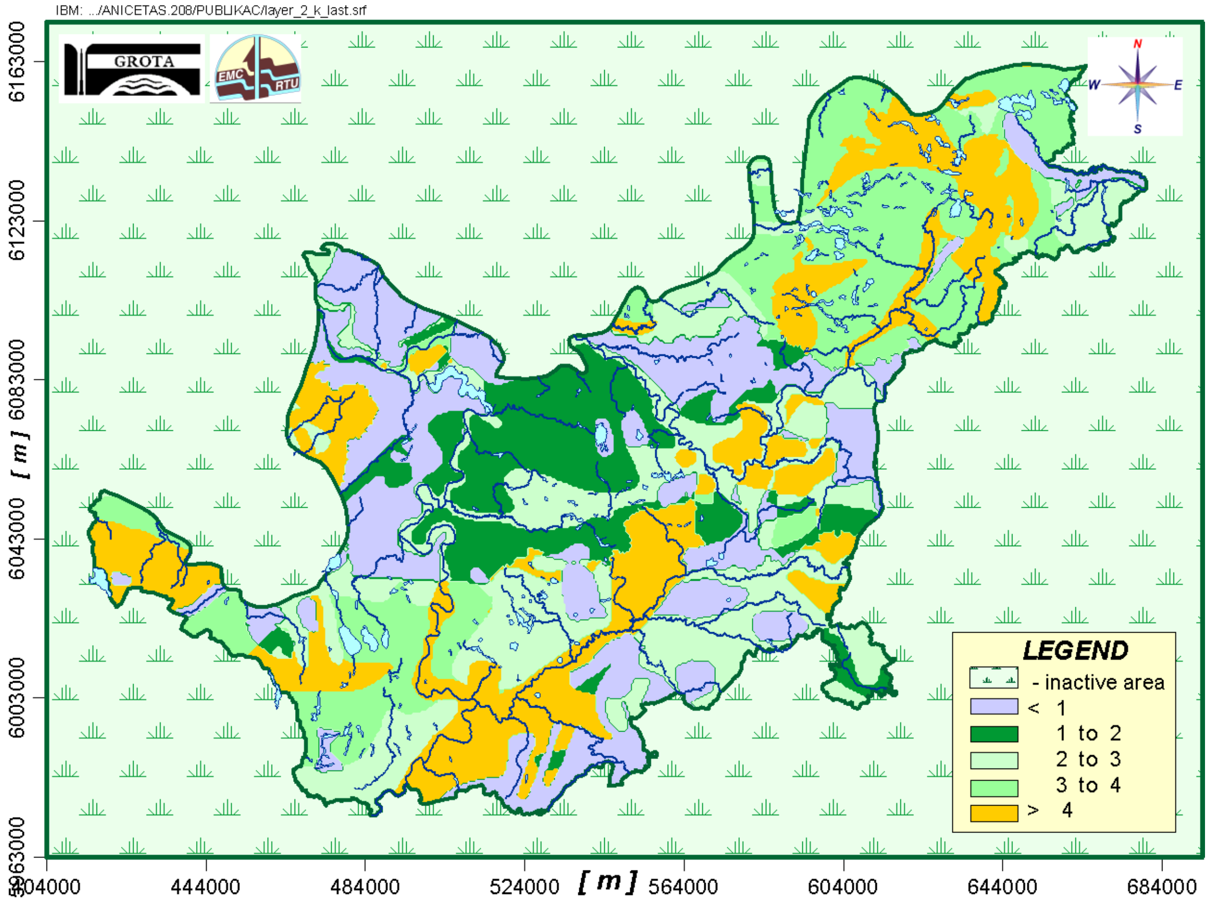

Fig. 5. Permeability distribution [10^{-4} m/day] of aeration zone

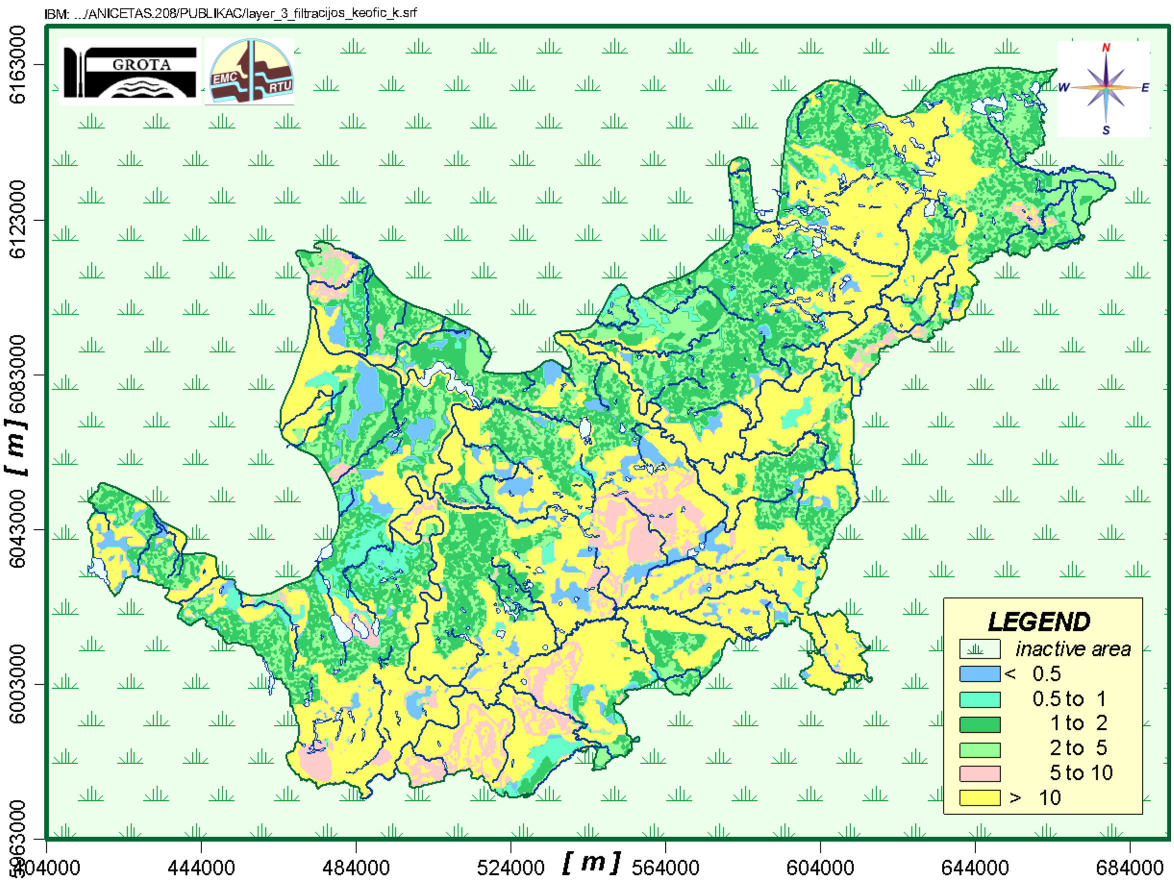

Fig. 6. Permeability distribution [m/day] of the layer 3

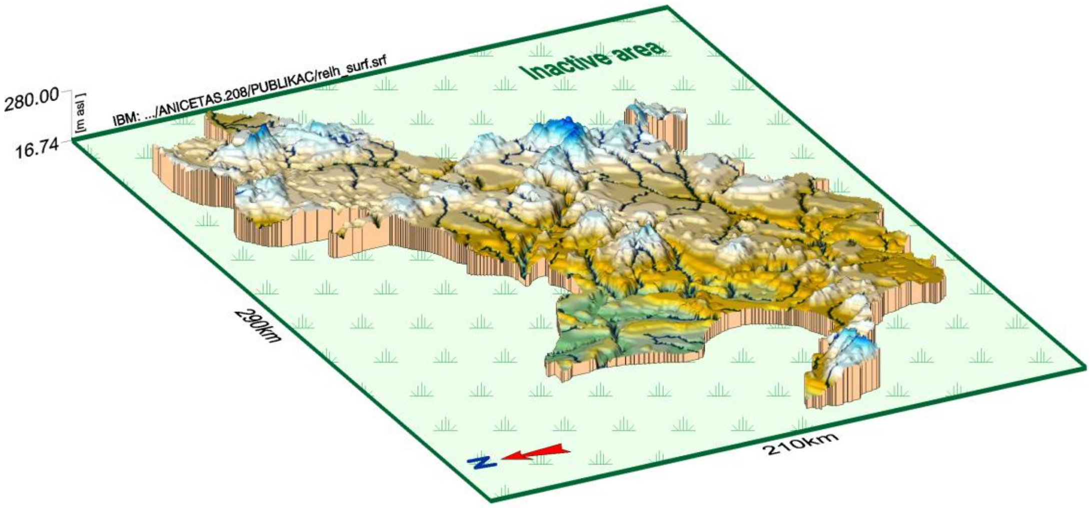

Fig. 7. Isometric image of the ground surface map as boundary condition of model top layer 1

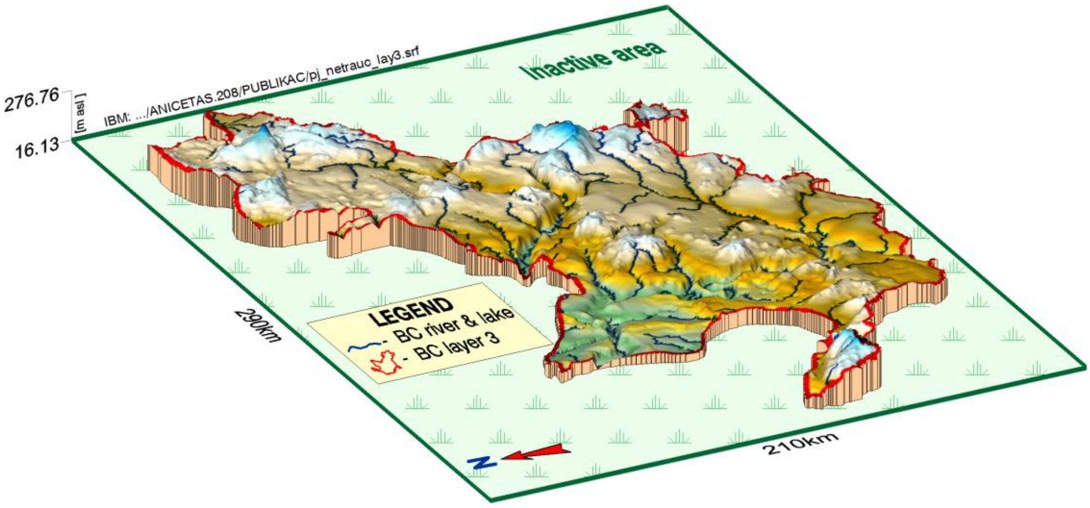

Fig. 8. Isometric image of modelled groundwater table (layer 3)

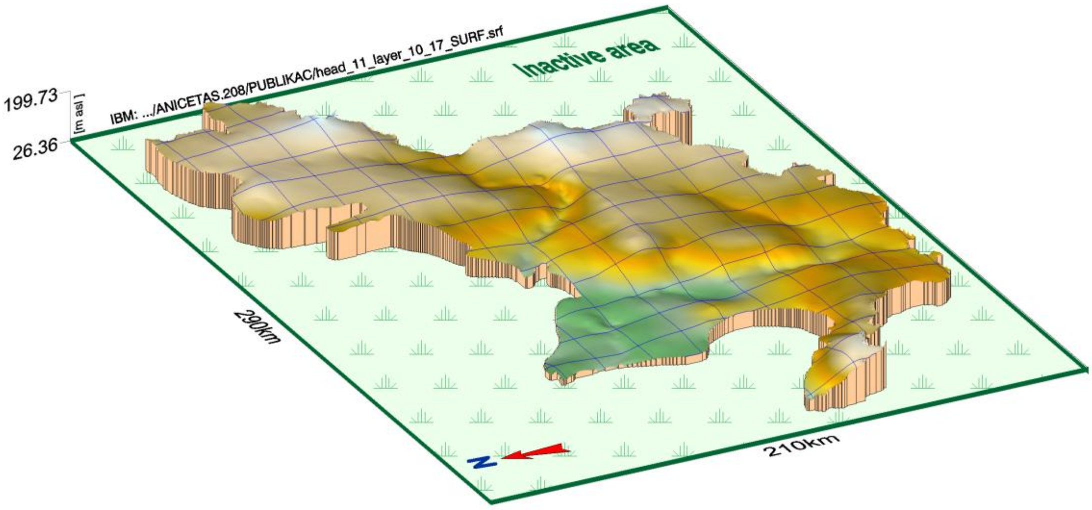

Fig. 9. Isometric image of the *pQ* map as boundary condition of model bottom layer 11

The system Surfer-8 [4] was applied for grid data calculations and for presenting graphical images of model results. Initial data, needed for HM creating, were prepared by the Joint Stock Company "GROTA".

The model is the steady state one. It simulates the mean annual hydrogeological situation.

Innovative methods were used to create HM. Due to them, the very complex model was built at a short time. Nature of these methods is explained and obtained results reported.

The project was financed by the Lithuanian government.

Basic mathematics of HM

To consider the process of HM creating, its basic matrix mathematics is presented by the following algebraic equation system:

$$A\varphi = \beta - G\psi, \quad A = A_{xy} + A_z \tag{1}$$

where φ is the solution vector (heads) at nodes of HM grid; A – the symmetric sparse matrix of the geological environment presented by the xy-layer system containing horizontal (A_{xy} – transmissivity) and vertical (A_z – vertical hydraulic conductivity) elements of the grid; ψ - the boundary head vector: ψ_{top}, ψ_{bot} and ψ_{bound} - subvectors on the HM top, bottom and borderlines, accordingly; G – the diagonal matrix (part of A) assembled by elements, linking the nodes where φ must be found with the ones where ψ is given; β - the boundary flow vector.

By using the 3D finite difference approximation, the xyz grid of HM is built using ($h\times h\times m$) - sized blocks (h is the block plane size; m is the variable thickness of a layer).

The elements a_{xy}, a_z of A_{xy} A_z (or g_{xy}, g_z of G) are computed by using the following formulas:

$$a_{xy} = k\times m,\; a_z = \frac{h^2\times k}{m}, \quad m_i = z_{i-1} - z_i > 0,\; i = 1,2,..s \tag{2}$$

where z_{i-1}, z_i are the elevations of the top and bottom surfaces of the i-th geological layer; z_0 represents the ground surface elevation map $\psi_{top} = \psi_{rel}$ with the hydrographical network included; k, m are, accordingly, elements of digital m, k-maps of the computed layer thickness and permeability; s – the number of layers.

The set of z-maps describes full geometry of HM. It is built incrementally: $z_0\rightarrow z_1\rightarrow\ldots\rightarrow z_S$ by keeping the thickness of the i-th layer $m_i > 0$. If in some areas $m_i = 0$, then the i-th layer is discontinuous. To prevent "division by zero", in the a_z calculation of (2), $m_i = 0$ must be replaced by $\varepsilon > 0$ (for example, $\varepsilon = 0.02$ metres). In GV, only the z-maps serve as the geometrical ones (no m-maps accepted).

Two tasks of the regional HM creating are the most burdensome ones: obtaining the right distribution for the infiltration flow β_{inf} on the HM top; building the set of z-maps.

For reported HM, these tasks were considerably eased, as follows:

- by using the ψ_{rel} -map, a feasible infiltration flow was obtained, as a part of the solved system (1);
- no real z-maps were applied, until the HM calibration was finished.

When ψ_{rel} is used, the flow $\beta_{aer} = \beta_{inf}$ passes through the aeration zone:

$$\beta_{aer} = G_{aer}(\psi_{rel} - \varphi_Q) \tag{3}$$

where φ_Q is the computed head (subvector of φ) for the first Q aquifer; G_{aer} (diagonal submatrix of G) contains the vertical ties g_{aer} of the aeration zone connecting ψ_{rel} with φ_Q. The expression (3) reflects the usual result of HM, when the ψ -condition is applied. As a rule, even the first run of HM provides surprisingly good results for β_{aer} that can be easy calibrated.

If no transport processes (migration of contaminants, particle tracking, etc.) are tried on HM, it is not necessary to apply its real geometry (z-maps). For reported HM, uniform flat layers of the thickness $m_c = 1.0$ were used. The real HM geometry was restored by applying the following grid data transformation for k_{xy}, k_z-maps, if the real m-maps were available:

$$k_{xy} = \frac{(km)_c}{m};\; k_z = \left(\frac{k_z}{m}\right)_c \times m \tag{4}$$

where $(km)_c$, $\left(\frac{k_z}{m}\right)_c$ - the calibrated values of transmissivity and of vertical leakance, accordingly.

The transformation (4) does not change flows and heads of calibrated HM.

Description of HM

The groundwater system, to be modeled, is highly irregular. Most of its aquifers and aquitards are discontinuous; numerous buried river valleys and hydrogeological windows are present, etc. (see Fig. 3).

To account for this complexity, HM contains 11 layers (planes). The plane approximation step $h = 500$ m was applied. Therefore, the HM grid plane contains 481×421 nodes, the 3D grid includes 2690611 nodes.

Boundary conditions of the ψ -type were applied on the top and bottom HM planes (1st. and 11th), on the borderline of the active HM area (planes 3, 5, 7, 9 of aquifers). The ψ_{rel} -map (see Fig. 7) carried by the plane 1 regulates the infiltration flow which distribution is highly irregular, on the HM area (see Fig. 4). The plane 2 represents the aeration zone as a formal aquitard with a variable permeability. Its distribution (see Fig. 5) was obtained during HM calibration. The plane 3 simulates the first unconfined Quaternary aquifer. Its computed head distribution is shown in Fig. 8. This distribution automatically follows the main geometrical features of ψ_{rel} (compare Fig.7 with Fig. 8). In humid areas, this natural phenomenon always occurs. The next three aquifers (planes 5, 7, 9) are the confined ones. The planes 4, 6, 8, 10 simulate aquitards that control vertical groundwater flows passing between aquifers. The hydrographical network was implemented in the plane 3 and in the plane 1 as a part of the ψ_{rel} -map. The HM bottom plane 11 carries the ψ_{pQ} -map that represents the pre-Quaternary piezometric heads (see Fig. 9).

To run the GV program, it is necessary to feed into it the following digital maps and data files: the surface elevation maps of digital layers (z-maps), the permeability maps (*k*-maps) of the layers, the boundary conditions for the planes 1 and 11 (ψ-maps), the ψ_{bound} data for the active area borderline (planes 3, 5, 7, 9), the groundwater withdrawal data β_w for well fields.

The task of creating the z-maps is the most burdensome one, because the topography of the geological strata is complex (see cross section *NS*, Fig. 3), and the data grid of these maps is rather coarse ($h = 500$ m).

To gain time for building correct z-maps, and not to postpone creating of HM, the uniform flat layer system was used instead of the real one.

Because all layers of this simplified HM version have the thickness $m_c = 1.0$, the transmissivity *km*-maps were used instead of the *k*-maps for creating elements of the matrix A_{xy}. For aquifers, the *km*-maps of good quality were available. For aquitards, the elements of A_{xy} were insignificant, because of the small permeability values ($10^{-2} > k_0 > 10^{-5}$) m/day of aquitards.

Unfortunately, no field data were available for the real aquitard permeability that determined elements of the matrix A_z. As the first try, the k_z-maps were used where $k_z = k/m$ (m – an expected thickness of a layer). In areas where $m = 0$, large values $k_z = 10^5$ m/day were applied, to connect tightly the neighboring layers.

Searching for the right k_z-maps of aquitards were the main object of HM calibration.

Finding and correcting errors occurring in the ψ and β-maps of boundary conditions were the first tasks to be done, because no calibration could eliminate this type of faults.

Calibration of HM

Due to unavoidable limitations in the initial data, HM has no unique solution. Calibration is a controlled iterative process involving the addition of complimentary data until as HM of required quality is obtained. The quality is checked and maintained by tracking calibration targets. The following targets are usually applied:

- original data should not be contradicted by data generated by HM; for example, the ψ and φ-distributions of (1) must reproduce observed head values; the subsurface runoff rate must confirm the measured one; the infiltration flow must match the observed one;
- results of HM must confirm the real hydrogeological situation, because formal agreement between computed and observed target data not always assures correct situation.

The first target group is formal, but the second one always requires subjective evaluation.

For the reported HM, "the complimentary data to be added during calibration" were the k_z-maps of five aquitards.

Two kinds of calibration targets were applied: the observed heads; the mean subsurface runoff rate of river basins.

In Tables 1 and 2 the calibration results for both groups of targets are presented. It follows from Table 1 that 823 monitoring wells were used as the calibration targets for four aquifers. Satisfactory match was achieved between observed and modeled heads. The standard deviation was within (2.49 - 3.08) metres; the relative deviation obtained as the "standard deviation/observed range" did not exceed 0.018 (1.8%).

Not all available head targets were used, because of the following reasons:

- the HM grid was not detailed enough ($h = 500$ m); in areas where the φ-distribution was steep, it could not reproduce the monitored heads correctly;
- in the vicinity of well fields, the head observations of previous years could not reproduce the modeled ones, because nowadays the water withdrawal rates had dropped considerably;

— considerable influence of the seasonal head changes, especially, for the first aquifer (plane 3).

It follows from Table 2 that HM satisfactory reproduces mean subsurface runoff rates for the six river basins. The maximal relative errors 6.0% and 13.5% were for the Neris and Sventoji basins, respectively.

Table 1

Target statistics for calibrated heads

Nr. of layer	Number of targets	Residual mean [m]	Standard deviation [m]	Observed range in heads [m]	Relative deviation [%]
3	357	-0.11	2.53	210.2	1.2
5	104	-0.41	3.08	190.5	1.6
7	189	-0.19	2.91	192.5	1.5
9	173	-0.46	2.49	138.8	1.8
Total	823				

Table 2

Subsurface runoff rate for river basins

River basin	Area of river basin in model [km^2]	Expected subsurface runoff rate [l/s km^2]	Modelled subsurface runoff rate [l/s km^2]	Difference [l/s km^2]	Relative error [%]
Neris	3529	3.80	4.030	0.23	6.0
Merkys	2860	5.16	5.18	0.02	0.6
Zeimena	2693	4.45	4.39	-0.06	1.4
Nemunas	6054	3.37	3.30	-0.07	1.9
Sesupe	1676	1.34	1.41	0.07	4.7
Sventoji	1186	2.82	2.46	-0.36	13.5

The calibrated HM state was achieved iteratively by adjusting k_z-maps of aquitards.

Calibrated HM also matched the present knowledge regarding the hydrogeological situation at the model area (the second group of targets).

Conclusions

The regional hydrogeological model has been built for the South-East of Lithuania. It simulates the Quaternary groundwater body that represents the main source of drinking water for this part of country.

The model was created by applying an innovative methodology that enabled to shorten the time for building of this very complex model.

The model is open for all possible improvements and it also serves as a base for creating local models of well fields, and for the areas where sanitation measures of contaminated places should be evaluated.

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A. Spalviņš, J. Šlangens, I. Lāce, A. Stuopis, A. Domasevicius. Reģionālā hidroģeoloģiskā modeļa izveide Lietuvas Dienvidaustrumu daļai
Izveidots reģionālais hidroģeoloģiskais modelis (HM) Kvartāra tipa pazemes ūdeņu sistēma, kura atrodas Lietuvas Dienvidaustrumu daļā. Šī sistēma pārklāj Lietuvas teritorijas vienu trešdaļu. HM taisnstūra formas laukuma izmērs ir 290km×210km. Seši lokālie upju sateces baseini veido HM aktīvo daļu, kurai ir neregulāra forma. Modeļa daļa, kura nav aktīva, nepiedalās aprēķinos. HM veidošanai izmantotas inovatīvas metodes: zemes virsmas augstumu karte kā pjezometrisko ūdens līmeņu robežnoteikumu, kurš noteica infiltrācijas plūsmu modeļa augšējai virsmai; aerācijas zona izmantota kā formāls sprostslānis; HM izveidošanas pirmajā posmā netika izmantota reālā ģeoloģisko slāņu ģeometrija. Šo inovāciju

izmantošana ļāva izveidot sarežģītu reģionālo HM ļoti īsā laikā, salīdzinot ar variantu, ja izmanto klasiskās metodes.

А. Спалвиньш, Я. Шлангенс, И. Лаце, А. Штуопис, А. Домашявичус. Построение региональной гидрогеологической модели для Юго-Восточной части Литвы

Построена региональная гидрогеологическая модель (ГМ) для Четвертичных водоносных структур, которые расположены в Юго-Восточной части Литвы. Эта структура покрывает одну треть Литвы. Прямоугольная область ГМ имеет размер 290км×210км. Шесть локальных бассейнов рек образуют активную часть ГМ, которая имеет нерегулярную форму. Остальная часть ГМ, которая не является активной, не участвует в моделировании. Для построения ГМ были использованы инновационные методы: для управления потоком инфильтрации на верхней поверхности ГМ, карта высот поверхности земли использовалась как граничное условие для пьезометрических уровней воды; зона аэрации использовалась как формальный водоупор. При реализации первого этапа построения ГМ, не использовалась реальная геометрия геологических структур. Благодаря этим инновациям, сложная региональная ГМ была построена за более короткое время, по сравнению с вариантом, когда применяются классические методы.