REGIONAL HYDROGEOLOGICAL MODEL OF LATVIA FOR MANAGEMENT OF ITS GROUNDWATER RESOURCES

AIVARS SPALVINS, JANIS SLANGENS, INTA LACE, OLGERTS ALEKSANS, KASPARS KRAUKLIS

Riga Technical University
emc@cs.rtu.lv

Abstract: *The countries of the world and of the European Union are developing hydrogeological models (HM) where, by means of computer modelling, the information necessary for the groundwater management is obtained. In 1996, Riga Technical University (RTU), upon assignment of the former State Geological Survey, established regional HM REMO for the central part of Latvia. REMO does not match demands of a modern water management for the whole country, the HM plane approximation step of 4000 meters is too crude. In 2010, RTU started the project of HM that includes the whole territory of Latvia and border areas of neighbouring countries. The project is co-financed by the European Regional Development Fund. HM accounts for 25 geological layers and its plane approximation step is 500 meters. HM have to be established, during 2010-2012, as the element of the Latvian Shared Environmental Information System. It is supported by the Latvian Environment, Geology and Meteorology Centre. HM will comprise geological and hydrogeological information provided by the centre. To ensure compatibility with models of other countries, the commercial program Groundwater Vistas is used for running HM. It contains software tools applied for groundwater modelling worldwide. For the establishment and calibration of HM, innovative methods are used: the map of the ground surface elevations (digital relief) serves as a boundary condition; the aeration zone is a formal aquitard; the actual geometry of HM may not be used in the initial phase of the model establishment. The model data will be used for regional evaluation of the groundwater flow distributions, especially, in areas bordering the neighbouring countries and the Baltic Sea. HM will provide data for establishment of local HM that are used for determination of the permissible productivity of well fields, for modelling contaminant migration and for evaluation of effectiveness of measures used for restoration of groundwater resources.*

Keywords: regional hydrogeological models, computer based modelling, MODFLOW

Introduction

The activity of Latvia in the surface water and groundwater resource management is defined by the Water Management Law (Latvijas Ūdens apsaimniekošanas likums, 2002) and by the subordinated regulations and orders of the Cabinet of Ministers. Latvia is implementing the aims laid down by the European Union (EU) Water Framework Directive (2000) for sustainable use of water resources. The Directive provides a unified procedure for the management of water resources in EU member countries:

- the use in conforming to natural laws the river catchment area principle; the territory of Latvia comprises four cross-border type river basins: those of Venta, Lielupe, Daugava and Gauja rivers;
- interdisciplinary approach to planning and its continuity; in Latvia three planning stages are foreseen: the years 2004- 2015, 2015- 2021 and 2021-2027.

At present, Latvia is in the first planning cycle. Some of its results are reflected in the document (Upju baseinu apgabalu raksturojums, 2005). The conditions of groundwater resources in Latvia, before it joined EU, are described in(I. Levins et al., 1998). In general, the groundwater resources in Latvia are in good condition. However, shallow groundwater is poorly protected from surface sources of pollution (waste dumps, territories of former military bases, oil product storage, agricultural activities, etc.). Incorrect and excessive use of groundwater has resulted in worsening of its quality (in Liepaja, sea water intrusion took place; in Jelgava, the quality of artesian groundwater is worsening, the well field Baltezers is endangered by economic activities in its vicinity, etc.).

Water management plans are drawn up and adjusted by the Latvian Environment, Geology and Meteorology Centre (LEGMC) upon assignment by the Ministry of Environmental Protection and Regional Development of the Republic of Latvia. The Centre has to establish and develop the shared environmental information system of Latvia that would also include water management.

The countries of the world: the USA (Motz, Gan, 2002), Canada (Sykes et al., 2007), Russia (Spalvins et al., 2001); and of EU: Denmark (Muller-Wohlfeinl and Mielbs, 2007), the Netherlands (Snepvangers et al., 2007), Great Britain (Farell, 2007), Lithuania (Spalvins et al., 2010), etc. are developing hydrogeological models (HM) of country and its regions where, by means of computer modelling, the information necessary for the water management planning is obtained (distributions of groundwater heads, stratigrafic cuts, characteristics of water filtration for geological layers, directions and velocities of groundwater flows, spread and volume of contaminants in groundwater, etc.).
In 1996, Riga Technical University (RTU), upon assignment of the State Geological Survey established the regional HM REMO for the central part of Latvia (Spalvins et al., 1996a). The data of the model has been used by the university for obtaining many local HM (Spalvins et al., 1996b), (Spalvins, 1998), (Spalvins et al., 1999), (Spalvins et al., 2008a), (Spalvins et al., 2008b), (Spalvins et al., 2009a), (Spalvins et al., 2009b).

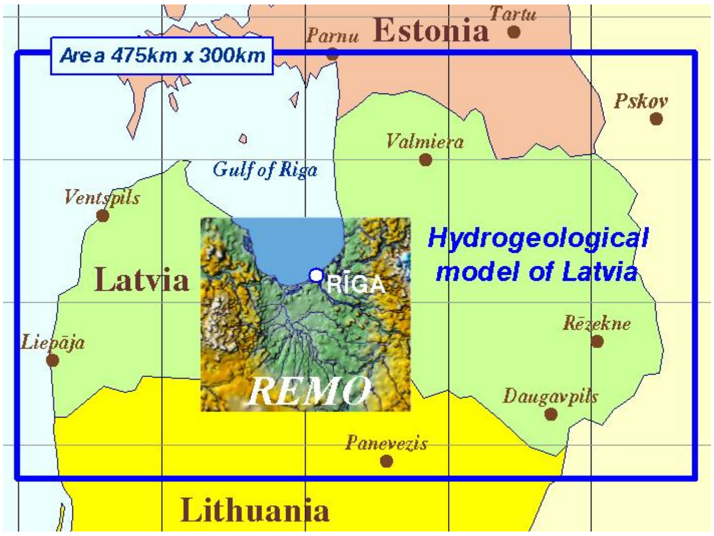

Fig. 1: Location of Latvia HM and REMO

At present, in the framework of the project co-financed by the European Regional Development Fund, RTU is developing HM for the whole territory of Latvia. Location of this model and REMO is shown in Fig. 1. HM of Latvia (LAMO) will be established as the element of the shared environmental information system of Latvia. LAMO will generalize geological und hydrogeological information accumulated by LEGMC. LAMO will be used for management of drinkable groundwater resources and for evaluating their recovery measures. To solve smaller scale problems, LAMO will serve as the data source for building more detailed local models. LAMO corresponds to requirements of the first planning stage of Latvia for the groundwater management. However, LAMO is open for its further development, as a tool to be used for the second stage.

Description of REMO and LAMO

LAMO covers the area of $475\text{km}\times300\text{km}=142500\text{km}^2$. Just like REMO, it will simulate the steady state average groundwater regimes for the area of active water exchange that is used in Latvia for drinkable water supply. The model is approximated by the spatial (3D) finite difference method; its plane approximation step is 500 meters; the spatial HM grid contains 25 planes (see Table 1); therefore, the grid consists of $951\times601\times25=14.86*10^6$ nodes; the active groundwater zone is bedded by the regional Narva aquitard.
The REMO plane approximation step was 4000 metres. Its spatial grid contained 10 planes for aquifers, because the cruder semi 3D finite difference method was applied (aquitards were not presented by planes but only by the vertical links joining adjacent aquifers). The REMO grid contained $43\times40\times10=17200$ nodes. Although, the semi-3D scheme reduces the number of the HM planes nearly twofold, this scheme is not fully conformable with the commonly used software tools (MODPATH, MT3D) that are based on particle tracing. To avoid this drawback, the 3D scheme is applied to LAMO.

Table 1

LAMO vertical schematisation

HM plane z		Name of layer	Geolo-gical code	HM plane code	HM plane name	HM border code	Comments
1.		Relief	relh	relh	Relief	bHM	boundary condition
2.		Aeration zone	aer	aer	Aeration zone	bHM	formal aquitard
3.		Unconfined Quaternary	Q4-3	Q2	Quaternary Q2	Q2	
4.		Upper moraine	gQ3	gQ2z	Upper moraine	gQ2	
5.		Confined Quaternary or Jura	Q1-3 J		Quaternary Q1	Q1	includes volumes of J
6.		Lower moraine or Triass	gQ1-3 T	gQ1#z	Lower moraine	gQ1	includes volumes of T
7.		Perma Karbons Skerveles Ketleru	P2 C1 D3šķ D3ktl	D3ktl#	Ketleru	D3ktl	
8.		Ketleru	D3ktl	D3ktlz	Ketleru z	D3ktlz	uncertain boundary
9.		Zagares Svetes Tervetes Muru	D3žg D3sv D3tr D3mr	D3zg#	Zagare	D3mr	
10.		Akmenes	D3ak	D3akz	Akmene	D3ak	
11.		Akmenes Kursas Jonisku	D3ak D3krs D3jn	D3krs#	Kursa	D3jn	
12.		Elejas Amulas	D3el D3aml	D3el#z	Eleja	D3aml	
13.		Stipinu Katlesu Ogres Daugavas	D3stp D3ktl D3og D3dg	D3dg#	Daugava	D3dg	
14.		Daugavas Salaspils	D3dg D3slp	D3slp#z	Salaspils	D3slp	
15.		Plavinas	D3pl	D3pl	Plavinas	D3pl	
16.		Plavinas Amatas	D3pl D3am	D3am#z	Amata z	D3amz	uncertain boundary
17.		Amatas	D3am	D3am	Amata	D3am	
18.		Upper Gauja	D3gj2	D3gj2z	Upper Gauja z	D3gj2z	uncertain boundary
19.		Upper Gauja	D3gj2	D3gj2	Upper Gauja	D3gj2	
20.		Lower Gauja	D3gj1	D3gj1z	Lower Gauja z	D3gj1z	uncertain boundary
21.		Lower Gauja	D3gj1	D3gj1	Lower Gauja	D3gj1	
22.		Burtnieku	D2brt	D2brtz	Burtnieku z	D2brtz	
23.		Burtnieku Arikula	D2brt D2ar	D2ar#	Arikula	D2ar	
24.		Narvas Narvas Narvas	D2nr3 D2nr2 D2nr1	D2nr#z	Narva	bHM	borderline of HM
25.		Pernavas	D2prn	D2pr	Pernava		boundary condition

#- united aquifer, #z- united aquitard, -aquitard

The whole REMO area (168km×156km=26208km^2) was active. At present, LAMO consists of its active and passive zones. The active zone includes the land territory of Latvia and area of the Gulf of Riga that is covered by REMO (see Fig. 2.). The passive zone represents border areas of neighbouring countries.

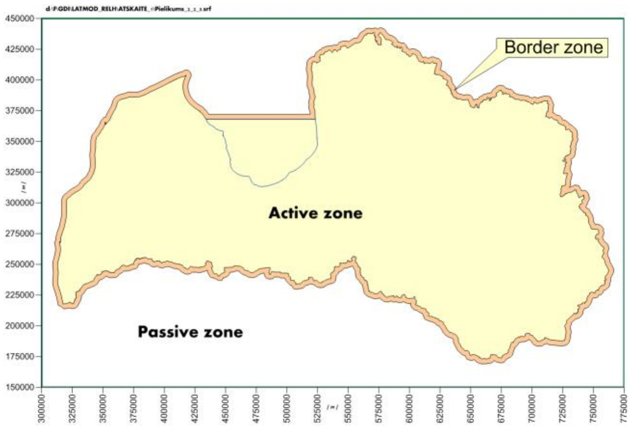

Fig.2. LAMO active and passive zones

However, LAMO is open for transboundary modelling projects. The neighbouring country provides data for activating the HM area involved. The active and passive zones are separated by 4 km wide border zone where piezometric boundary conditions for aquifers can be fixed.

For running REMO, an original modelling program was used. It was developed by RTU scientists. If RTU scientists did not participate in the project, the State Geological Survey would be incapable of supporting and using REMO. Unfortunately, the survey lost active interest in REMO (the decision was taken to use the Daugava River as the extra source of drinking water for Riga) and only RTU scientists had successfully used REMO, until now. To avoid the above mentioned difficulty, the commercial program "Groundwater Vistas" (GV) is used for running LAMO (Environmental Simulations, 2011). The program is being regularly updated (the GV-6 version is available). It contains software tools MODFLOW, MODPATH, MT3D that are applied for groundwater modelling worldwide. The GV system is generally used also in Latvia. Due to application of GV, results of LAMO will be available for public use in Latvia and the LAMO compatibility with HM of other countries will be more possible.

LAMO vertical schematization is presented in Table 1. For the planes 12-25, it coincides with he one of REMO. In REMO, instead of the planes 7-11, the united Famena aquifer (D3fm#) was used for the central part of Latvia. For LAMO, these five planes represent the geological layers of the South-West of Latvia.

In REMO and LAMO, the planes 1 and 2 are used, accordingly, as a place for fixing the relief deviation map as the piezometric boundary condition and as a formal aquitard that controls the infiltration flow distribution (Spalvins et al., 2011a). For more information, on these issues see section "Methods of HM Development". In REMO, the Quaternary system was represented by two planes (unconfined Q_2 and the moraine gQ_{2Z}). Four planes for this system are used in LAMO, because two extra layers are accounted (confined Q_1, lower moraine gQ_{1Z}). These two layers are of importance to the hilly areas of Latvia where the Quaternary system is thick. In LAMO, no separate layers are given for representation of the Jura and Triass systems. They are incorporated into the HM layers 5 and 6, accordingly, because their areas are insignificant (South-West of Latvia).

Most of geological layers, comprised by REMO and LAMO, are discontinuous (see also comments on Table 1). Discontinuity of the layers and their irregular geological borderlines cause serious problems for building elevation surfaces of the layers (Spalvins et al., 2011b).

Methods of HM Development

To describe development of HM, the mathematics of the 3D-steady state model must be introduced. By applying the 3D finite difference approximation, the xyz-grid of HM is built using (h×h×m)-sized blocks (h is the block plane size, m is the variable thickness of a geological layer). The model constitutes a rectangular p-tiered xy-layer system where p is the number of layers. Four vertical sides compose the shell of the HM grid. The relief (ground surface) and the lower side of the model are its geometrical top and bottom, respectively. The 3D-space volume enveloped by the boundary surfaces constitutes the body of HM. For the LAMO active part, its shell coincides with the border zone that separates HM active and passive parts. However, the GV system accounts for the whole body of HM.

The vector φ of the piezometric head is the numerical solution of the boundary field problem which is approximated in nodes of the HM grid by the following algebraic expression:

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

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

The elements a_{xy}, a_z of A_{xy}, A_z (or g_{xy}, g_z of G) are computed, as follows:

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

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

The set of z-maps describes the full geometry of LAMO. It is built incrementally: $z_0 \rightarrow z_1, \ldots, z_p$ 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 the "division by zero", in the a_z calculation of (2), $m_i=0$ must be replaced by $\varepsilon > 0$ (for HM, $\varepsilon=0.02$ metres). In GV, only the z-maps serve as the initial geometrical ones. For REMO, the set of m-maps were used and, due to this reason, the model geometry was of lower quality than the geometry resulting from the z-maps.

Obtaining the right distribution for the infiltration flow β_{inf} on the HM top is a burdensome task. For REMO and LAMO, this task is considerably eased by using the ψ_{rel}-map as the boundary condition for heads. Then the flow $\beta_{inf}=\beta_{aer}$ 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 aquifer Q_2; 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) gives the standard result of HM, when a ψ-condition is applied. As a rule, even the first run of HM provides feasible results for β_{inf}.

The vertical links, g_{aer} of the diagonal matrix G_{aer}, are controlling the $\beta_{aer}=\beta_{inf}$ distribution. Values of g_{aer} depend on h^2, k_{aer} and m_{aer} (formula (2)) where k_{aer} , m_{aer} are, respectively, the permeability and thickness of the aeration zone. Initially, k_{aer} and m_{aer} are unknown. In nature, $m_{aer}=\varphi_{rel}-\varphi_{Q2}$ if $\beta_{aer}>0$ and it is the unsaturated part of the unconfined layer Q_2. If $\beta_{aer}<0$ then m_{aer} ceases to exist, because then $\beta_{aer}<0$ is controlled by bed conductances of the hydrographical network. Formerly, these conductances were elements of G_{aer}. Just recently, the lines and areas of the network have been implemented as the "Rivers" and "Lakes" options of GV. (Spalvins et al., 2009b). This innovation will be used in LAMO. First, the following values of the unknown parameters of the aeration zone for LAMO will be tried: $m_{aer}=\varepsilon=0.02$, $k_{aer}=10^{-6}$ [m/day]. To avoid iterative changes of the HM geometry, $m_{aer}=\varepsilon$ must be kept constant, until the calibrated state of HM is achieved by adjusting the k_{aer} – distribution.

Therefore, for LAMO, only two real thicknesses m_{aer} and m_{Q2} must be restored, if necessary. It can be done by applying the "inverse" transformation of the calibrated $(k_{aer})_c$ and $(k_{Q2})_c$–maps:

$$k_{aer}=(k_{aer})_c\, m_{aer}/\varepsilon, \qquad k_{Q2}=(k_{aer})_c\,(m_{Q2})_c/m_{Q2}, \qquad m_{Q2}=(m_{Q2})_c-m_{aer}, \tag{4}$$

where $\varepsilon=0.02$ and $(m_{Q2})_c$ are the thicknesses used during the HM calibration. The transformation results from formulas (2), because this operation does not change the calibrated values of the matrix A elements a_{xy} and a_z.

On the much broader scale, this transformation has been applied for creating HM of the South-East Lithuania (Spalvins et al., 2010). This model was started and calibrated by using equal thicknesses m=1.0 for all nine geological layers of HM (no z–maps were used, to run HM).

For geological layers, their geometrical thickness is $m \geq m_{ef}$. The effective thickness m_{ef} accounts for the fact that, not always, the layer permeability is isotropic. Aquifers and aquitards may include admixtures, accordingly, of low and high permeability. Because the HM geometry results in the thickness m-maps, the original k_{xy}, k_z-maps must be corrected, as follows:

$$\begin{aligned} (k_{xy})_c &= k_{xy} \times C,\ (k_z)_c = k_z \times C^{-1}, \\ c_i &= \left(m_{ef} \times m^{-1}\right)_i \leq 1.0 \end{aligned} \qquad (5)$$

where $(k_{xy})_c$, $(k_z)_c$ are the corrected permeability values; C is the diagonal correction matrix which is obtained by interpolating borehole data on the xy-grid planes of HM; c_i – the i-th initial element of C given by a borehole. The algorithm (5) has been first used to create HM of a new well field (Spalvins et al., 2009a).

In REMO, the effective thicknesses m_{ef} were formed by changing the HM geometry when the m-maps were obtained. This method results in serious faults of the HM geometry. Due to this reason, for LAMO, the correction of (5) will be used.

Initial Data for Developing LAMO

Geological and hydrogeological data for developing LAMO were provided by LEGMC. Information regarding the ground relief of Latvia and its hydrographical network was taken from the Geospatial Information Agency of Latvia (GIAL).

The data provided by LEGMC in the digital form were, as follows:

- information carried by geological wells (stratigraphy of geological layers and their filtration characteristics (water permeability k);
- digital maps of some geological layer surfaces; the most important were two maps for the whole territory of Latvia: the subquaternary subQ surface (bottom of the Quaternary system; (plane z=6 of HM) and the bottom surface of the Narva aquitard (plane z=24 of HM);
- the set of borderlines for geological layers;
- arrangement and productivity of the groundwater extraction wells (information for the vector β of (1));
- data provided by monitoring wells where regular measurements of groundwater heads are done; the data are used for the HM calibration purposes and for obtaining values of the vector ψ of (1);
- other information, in the paper form, including the Geology Fund archive materials.

The information on geological wells, involve a high degree of uncertainty, as the arrangement of wells is irregular, their depth is different, their data, as a part of HM, have not been verified. The data contain essential errors (incorrect attachment to ground surface, erroneous plane coordinates, not all geological layers are mapped, etc.). The above mentioned errors may be detected and sometimes prevented only during the creation of HM. Gaps in information on wells can be partially prevented by examining materials from geological data archives where specialists have provided the analysis of hydrogeological situations. However, also archive materials are not always qualitative.

Information on the permeability k of geological layers is very incomplete even in respect to aquifers. The k–distribution for aquitards is unknown and it must be found by calibrating the model.

Obtaining the digital relief map ψ_{rel} of Latvia (scale 1:200000), as the most important item of LAMO was a rather difficult task, because the maps prepared by GIAL still did not account for the hydrographical network existence. In the materials (Slangens et al., 2010; Slangens et al., 2011) it is shown how the considerably improved ψ_{rel} map has been created (see Fig. 3). The map provides three types of information: a) the geometrical top surface z=o; b) the distributed piezometrical boundary condition ψ_{rel} ; c) the hydrographical network data (long line profiles of rivers and elevations of lakes) that are used by the options “Rivers” and “Lakes” of GV.

, The *subQ* surface is shown in Fig. 4. It was slightly corrected by RTU scientists when the thickness distribution of the Q system was obtained. No extra incisions into the *subQ* surface were allowed. Due to this fact, some special corrections have been made for the surface z=1 plane. They are described in (Spalvins et al., 2011b).

The *D2nr* bottom surface (z=24) is shown in Fig. 5. It has been accepted by RTU scientists without making any corrections in the map prepared by specialists of LEGMC.

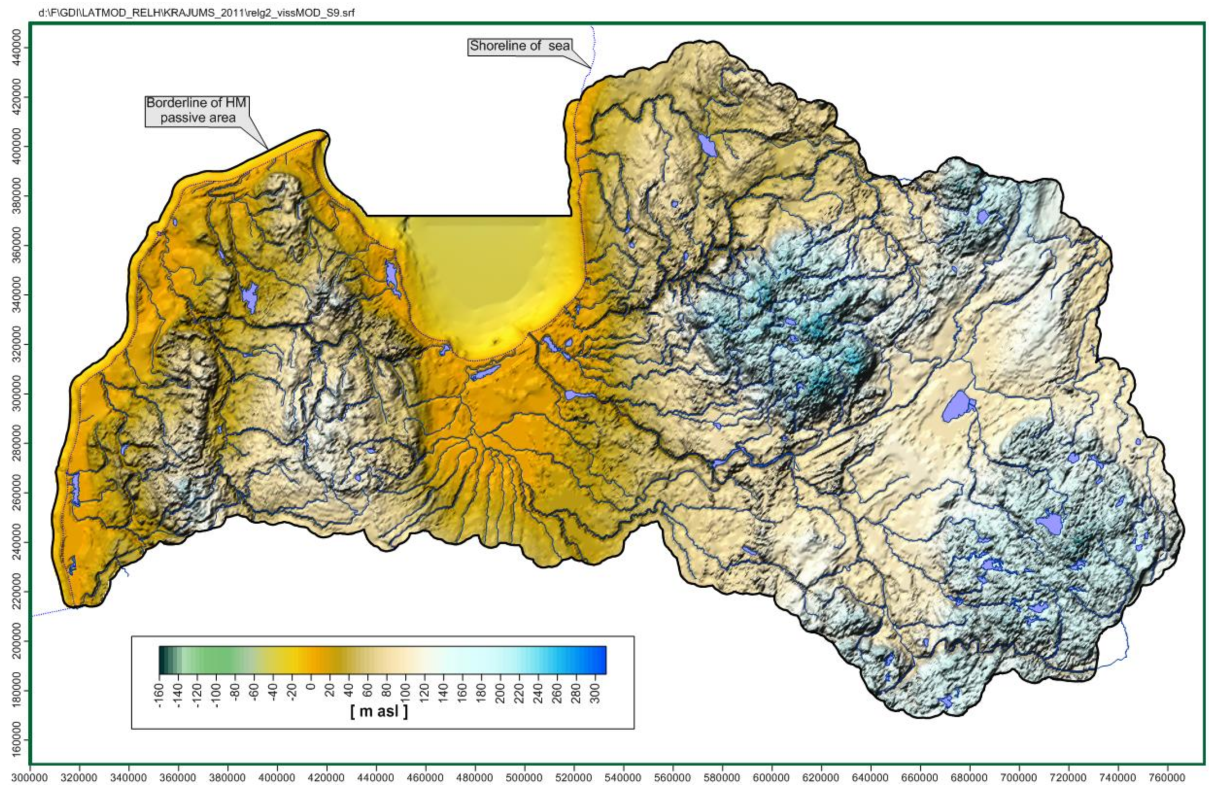

Fig. 3. **The digital relief ψ_{rel} used in LAMO**

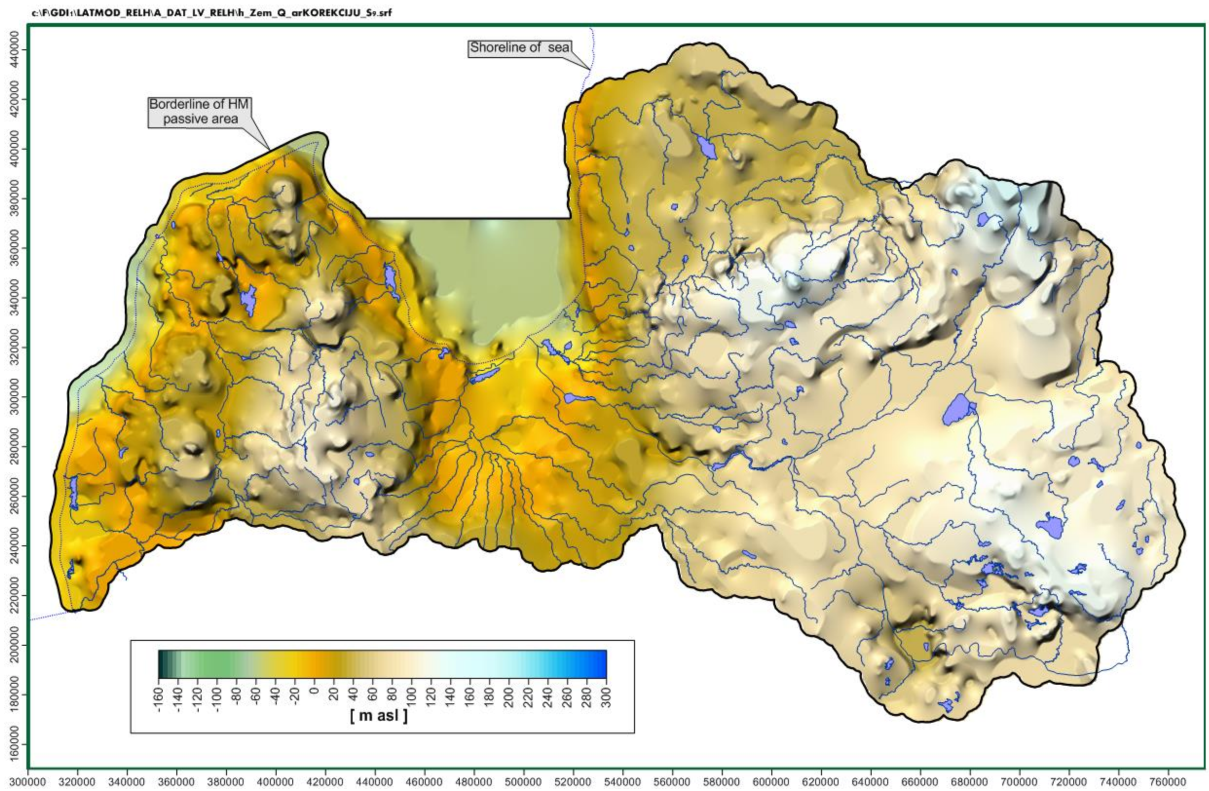

Fig. 4. **The subquaternary surface used in LAMO**

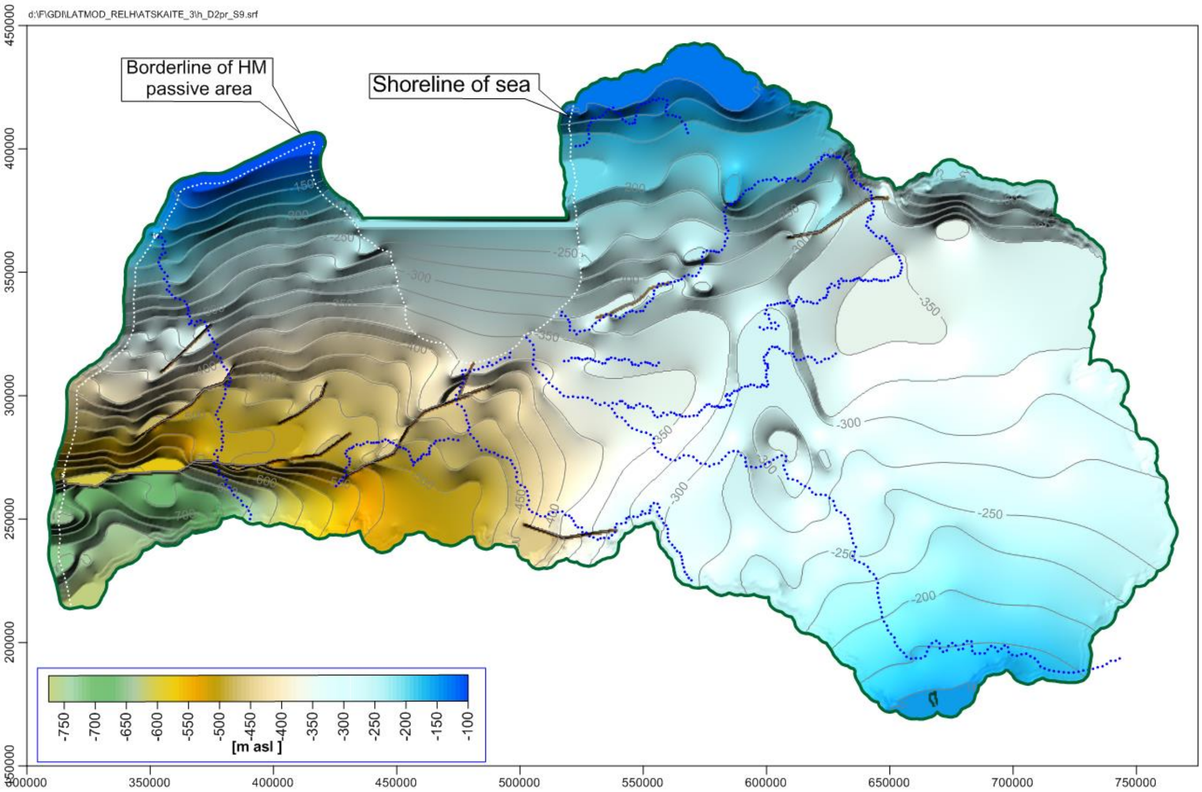

Fig.6. **The bottom surface of the aquitard D2nr#**

Stages of LAMO Development

Stages of the LAMO development are as follows:

- preparation of set of initial data;
- creation of the model digital map set;
- creation and calibration of the model.

The most time-consuming is the process of elaboration of the z–maps. To elaborate these maps, RTU scientists use the original GDI program (Spalvins et al., 2007; Spalvins et al., 2004) that mostly apply line-type data sources.

After all the necessary digital maps have been uploaded into the GV system, the model starts functioning and its calibration has to be accomplished.

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

- 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 matrix A must incorporate observed permeability and geometrical features of k, z–maps, etc.;
- within the HM body, groundwater flows should not reach unnaturally large values (infiltration flow, flows regarding the hydrological network, etc.);
- results of HM must confirm the real hydrogeological situation, because formal agreement between computed and observed target data does not assure correct simulation; unfortunately, automatic calibration tools can sometimes provide almost worthless results.

The first and second targets are formal components of HM, but the third target always requires subjective evaluation.

The calibration will never succeed if serious HM errors are present. Problems can include faults in data coordinate or values, mistakes in geological layer identification, mismatched reference data, unreliable boundary conditions or inadequate software.

Where initial data have not been previously used for modelling (most of data, to be used for LAMO, belong to these data, their role can be unclear and their validity may be questionable (especially, the stratigraphical data of boreholes).
However, to create and calibrate HM, RTU scientists are going to apply already tested sophisticated methods and software tools, in order to overcome possible problems regarding quality of initial data.

Conclusions

During two years (till 2012) scientists of Riga Technical University should establish the regional hydrogeological model of Latvia. The model will be applied as the element of the shared environmental information system. To create the model RTU scientists are going to use innovative methodology and software tools. The following main innovations will be used:

- the improved method of creating infiltration flow;
- the method for accounting for the effective thicknesses of geological layers;
- the method that enables not to use the real geometry of HM (at least, in the beginning);
- improved original software tools for interpolation of geological and geometrical data;
- the method enabling to find data needed to create the hydrological network of HM.

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