Survey of Methods Used to Develop the Hydrogeological Model of Latvia

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Abstract – **In 2010–2012, the hydrogeological model (HM) of Latvia LAMO was established by scientists of Riga Technical University (RTU). The commercial program Groundwater Vistas (GV) is used for running LAMO. Efficient methods have been used for creating geometry of HM, the arrangement of various boundary conditions (digital terrain map, hydrographical network, infiltration flow, conditions on the HM shell surface) and for calibrating HM. Their application has considerably improved the quality of HM and reduced time needed to create LAMO.**

Keywords – **Boundary conditions, finite difference approximation, regional hydrogeological model.**

I. Introduction

This publication is focused on survey of methods [1], [2], [3] used to create LAMO. LAMO simulates the steady-state average hydrogeological situation of Latvia. LAMO covers the area of 475km–300km (Fig. 1). For the current LAMO version, the land territory of Latvia and the area of the Gulf of Riga constitute the HM active area (Fig. 2). The passive area represents border territories of the neighbouring countries. The active and passive areas are separated by the wide border zone of 4km, where boundary conditions for the active area are fixed. LAMO is open for transboundary modelling projects. The neighbouring country must provide data for activating the passive HM area involved. The vertical schematisation of LAMO is shown in Fig. 3, where geological layers are represented of the drinkable groundwater zone of Latvia. The planes 1 (rel) and 27 (D2pr) are used as places for fixing piezometric boundary conditions. The plane 2 (aer) serves as a formal aquitard that controls the computed infiltration flow. The Quaternary system and the primary Devonian layers are represented, respectively, by the planes 3-6 and 7-27. No separate layers account for the Jura and Triass systems. They are incorporated into layers 5 and 6, respectively.

To describe methods used for establishing LAMO, the basic mathematics of 3D steady-state models must be considered. By applying finite difference approximation, the *xyz*–grid of HM is built using ($h{\times}h{\times}m$) sized bocks (*h* is the block plane size, *m* is the variable thickness of a geological layer). The model constitutes a *p*–tiered *xy*–layer system. For LAMO, *p*=27, *h*=500 metres. The 3D body of LAMO is approximated by the xyz–grid of the size 951×601×27.

The modelling program controls the whole area of HM that contains also the passive area that takes no part in simulation. The active HM volume is enveloped by the border zone. Its outer vertical surface represents an impermeable shell that blocks a transboundary groundwater flow. Due to this fact, the
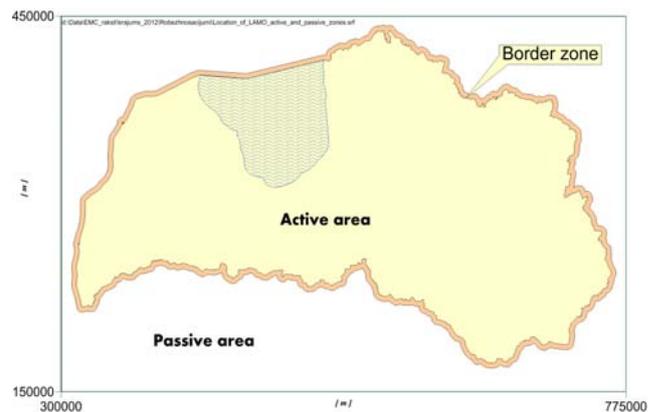

Fig. 1. Location of LAMO.

Fig. 2. Location of LAMO active and passive areas.

groundwater regime there gets distorted and axillary boundary conditions must be used to restore the normal regime.

Vector φ of the piezometric head is the numerical solution of the boundary field problem, which is approximated in nodes of the HM *xyz*–grid by the following algebraic expression:

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

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_{out} ψ_{riv} –subvectors of ψ that represent boundary conditions of the HM top, bottom, border zone and rivers, respectively; *G* – the

diagonal matrix (part of *A*) assembled by elements, linking the nodes, where φ must be found with the points, where ψ is given (for ψ_{top}, ψ_{bot}, ψ_{out} these points are nodes of the HM grid); 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:

$$a_{xy} = k\,m, \quad a_z = (h^2\,k)/m, \quad m_i = z_{i-1} - z_i\,, \quad i = 1, 2,\ \ldots, p \quad (2)$$

where z_{i-1}, z_i are elevations, respectively, 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, respectively, elements of digital *m*, *k*-maps of the computed layer thickness and permeability.
If in some areas $m_i=0$, then the *i*-th layer is discontinuous. To prevent the "division by zero", in (2), $m_i=0$ must be replaced by small $\varepsilon > 0$ (for LAMO, $\varepsilon=0.02$ metres).

The set of *z*−maps represents the geometry of LAMO. The creating of these maps is the most burdensome task, because geometry of the geological environment of Latvia is very complex [4]. For the GV system [5], only z-maps serve as the initial ones and m-maps (thicknesses of layers) are obtained by GV itself. Appliance of *z*−maps is preferable, because it results in more accurate geometry of HM.

In LAMO, the β−vector of flows is represented only by the withdrawal rates β_w of wells. It is not applied to the simulation of flows on the HM top and on other boundary surfaces.

The ψ −conditions were applied, instead of the β−flows, due to the two main reasons:
- the ψ−conditions shortened the time needed for solving of (1), because they increased impact of the matrix *G* as the diagonal dominance factor of *A* [6, 7];
- numerical values of the ψ−conditions were known much better than the ones of the β−flows.

Boundary conditions ψ_{rel}, ψ_{out} ψ_{riv} are the most important ones. Their arrangement is commented in Section III.

II. INTERPOLATION OF DATA

For the z, k−maps, interpolation surfaces represent geometrical images. Initially, for creating these maps, the RTU team used popular interpolation methods: Criging, Minimal Curvature, and Inverse Distance. Unfortunately, these methods sometimes provided erroneous results [17]. For example, if an m distribution was highly irregular, negative thicknesses appeared, even if the input data were always positive. This failure occurred, because:
  • interpolated results did not hold the principle that output should remain within the minima and maxima of the input data;
  • the interpolation surface did not carry "minimal energy";
  • initial data were often ignored by algorithms applied for smoothing of the interpolation result.

As conventional methods did not provide controllable interpolation results, the GDI program was developed [8], [13], [17], [18]. It gives the interpolation surface σ, as the numerical solution of the following associated 2D boundary problem,

No of HM plane		Name of layer	Geological code	HM plane code
1.		Relief	relh	relh
2.	▨	Aeration zone	aer	aer
3.		Unconfined Quaternary	Q4-3	Q2
4.	▨	Upper moraine	gQ3	gQ2z
5.		Confined Quaternary or Jura	Q1-3 J	Q1#
6.	▨	Lower moraine or Triass	gQ1-3 T	gQ1#z
7.		Perma Karbons Skerveles Ketleru	P2 C1 D3šk D3ktl	D3ktl#
8.	▨	Ketleru	D3ktl	D3ktlz
9.		Zagares Svetes Tervetes Muru	D3žg D3sv D3tr D3mr	D3zg#
10.	▨	Akmenes	D3ak	D3akz
11.		Akmenes Kursas Jonisku	D3ak D3krs D3jn	D3krs#
12.	▨	Elejas Amulas	D3el D3aml	D3el#z
13.		Stipinu Katlesu Ogres Daugavas	D3stp D3ktl D3og D3dg	D3dg#
14.	▨	Daugavas Salaspils	D3dg D3slp	D3slp#z
15.		Plavinu	D3pl	D3pl
16.	▨	Plavinu Amatas	D3pl D3am	D3am#z
17.		Amatas	D3am	D3am
18.	▨	Upper Gauja	D3gj2	D3gj2z
19.		Upper Gauja	D3gj2	D3gj2
20.	▨	Lower Gauja	D3gj1	D3gj1z
21.		Lower Gauja	D3gj1	D3gj1
22.	▨	Burtnieku	D2brt	D2brtz
23.		Burtnieku	D2brt	D2brt
24.	▨	Arikula	D2ar	D2arz
25.		Arikula	D2ar	D2ar
26.	▨	Narvas Narvas	D2nr2 D2nr1	D2nr#z
27.		Pernavas	D2prn	D2pr

▨ - aquitard

-united aquifer;   #z − united aquitard

Fig. 3. Vertical shematization of LAMO.

solution of the following associated 2D boundary problem, on the xy–grid in system (1):

$$div(\lambda\ grad\ \sigma)=0, \tag{3}$$

$$V\ \sigma = -G_\sigma\ \sigma_\psi, \qquad V = V_{xy} - G_\sigma \tag{4}$$

where (4) is the algebraic equation system applied to approximate the problem (3); the matrices V_{xy}, G_σ represent, respectively, the horizontal links v_{xy} of the interpolation grid and the elements g_σ connecting nodes, where σ must be found with the ones, where σ_ψ are known as initial data σ_{in} for the interpolation. The parameter $\lambda(x,y)$ is used for controlling the shape of $\sigma(x,y)$. In areas where $\lambda=1$, point values σ_{in} usually produce sharp maxima. If $\lambda\gg1$ then the maxima becomes flat. Due to the changeable $\lambda(x,y)$, it is possible to modify the "strength" for each initial data source σ_ψ.

Fortunately for interpolation, σ always meets the maximum / minimum and minimal energy principles, as the fundamental feature of any solution of (3).

The GDI program mostly applies various line data as the initial ones, because they are much more informative than the pointwise data, on which the lines are based. For example, information carried by the long line profile of a river is far richer than the measured water levels of the river applied for obtaining the profile.

In GDI, any line can also be used as an impervious border, if necessary (masking of polygons, etc.).

An original program CRP has been developed for preparing the line data (isolines, geological borderlines, data of hydrographical network) and converting them into the initial data σ_ψ of the GDI program [19].

The GDI program is mainly applied to the sequential mode. During the current interpolation step, new information is used, but the results of the previous step serve as the base. In this way, a much simpler set of initial data can be applied than if one tries to obtain the final result at once. To create very complex maps, even small sets of initial root data are sufficient.

Unlike most of interpolation methods, the surface created by GDI may include sharp edges that very often are part of z–maps (tectonic faults, etc.).

III. ARRANGEMENT OF BOUNDARY CONDITIONS

A. *The Digital Relief Map and the head Distribution of the D2pr Aquifer*

Application of the piezometric boundary condition ψ_{rel} to the HM top, instead of the conventional β_{inf}–conditions for infiltration, has considerably reduced the effort of developing large regional models, where the infiltration distribution is very complex. It must account for numerous recharge and discharge areas. If HM contains many geological layers then it is virtually impossible to predict the response of HM to a fixed β_{inf} and the computed value of φ often occurs above the ground surface ψ_{rel}.

The ψ_{rel}-map was obtained by using the data of the Geospatial Information Agency of Latvia. Methods used to create the map are described in [9]. The GDI program was applied to account both for ground surface elevation isolines and parameters of the hydrographical network.

If the ψ_{rel} − map is used, the flow $q_{inf}=q_{aer}$ passes through the aeration zone:

$$q_{aer}=G_{aer}(\psi_{rel}-\varphi_{Q2}) \tag{5}$$

where φ_{Q2} is the computed head (subvector of φ) for the aquifer Q_2; G_{aer} (diagonal submatrix of G) contains the vertical links g_{aer} of the aeration zone connecting the fixed ψ_{rel} with the computed φ_{Q2}. The expression (5) gives the ordinary result of HM, when ψ-conditions are applied. As a rule, even the first run of HM provides the following feasible results:

- the surface φ_{Q2} automatically follows main geometrical features of ψ_{rel}, because g_{aer} interlinks both surfaces; in humid areas this natural phenomenon always occurs;
- it follows from (5) that components of q_{aer} respond correctly (q_{aer} increases) to a decrease of φ_{Q2} caused by the flow of wells β_w; when fixed β_{inf} is used, this natural response is not automatically accounted for;
- HM provides the q_{aer} distribution, which defines variable infiltration intensity and clearly indicates the areas of discharge and recharge.

The advantage of q_{aer} obtained by HM itself over a conventional fixed β_{inf} distribution is considerable, because q_{aer} is based on much more reliable initial data than any fixed β_{inf} distribution. The data are carried mostly by ψ_{rel} and the system (1), as a whole.

The vertical links g_{aer} of the diagonal matrix G_{aer} are controlling the q_{aer} distribution. Values g_{aer} depend on h^2, k_{aer} and m_{aer} (formula (2)); k_{aer} and m_{aer} are, respectively, the permeability and the thickness of the aeration zone. Initially, k_{aer} and m_{aer} are unknown. In nature, $m_{aer}=\psi_{rel}-\varphi_{Q2}$ if $q_{aer}>0$. If $q_{aer}<0$ then, in LAMO, $m_{aer}=0.02$. The negative infiltration flow is caused mainly by lowlands, rivers and lakes. First, the following values of the aeration zone were tried: $m_{aer}=0.02$ [m], $k_{aer}=10^{-6}$ [m/day] (for recharge areas); $k_{aer}=10^{-4}$ [m/day] (for areas of lakes and sea); $k_{aer}=10^{-8}$ [m/day] (for areas of swamps).

To avoid iterative changes of the HM geometry, during calibration of HM, $m_{aer}=0.02$ was kept constant, until the calibrated q_{aer}–flow was obtained (Fig. 7) by adjusting the k_{aer}–distribution. This uncommon assumption is permissible. It was explained in [1], [20] that in order to avoid any change of the geometry, the real thicknesses of layers (in our case, m_{aer} and m_{Q2}) may not be applied during calibration.

The piezometric head distribution ψ_{D2pr} of the D2pr aquifer is applied as the boundary condition to the LAMO bottom plane ($p=27$). The ψ_{D2pr}-map was obtained by using information of [16]. Influence of ψ_{D2pr} is small, because it is separated from the HM body by the thick regional D2nr aquitard (see Fig. 4).

There are two reasons for application of this boundary condition: it may be useful if a modeller carries out research regarding the role of tectonic faults of the D2nr aquitard; the D2pr aquifer contains drinking water in the northeast part of Latvia.

B. Design of Boundary Conditions for the Border Zone

Due to the presence of the HM passive area, the outer vertical surface of the boundary zone (shell) is impermeable for the transboundary groundwater flow. This causes distortion of the natural groundwater regime at the vicinity of the shell. One must try to recover the regime on the inner surface of the border zone. It can be done by fixing auxiliary boundary conditions ψ_{out} on the middle line of the zone. As the initial data for obtaining ψ_{out} of aquifers, three data sources were used that provided linewise information (as slices along the zone middle line): the ψ_{rel} −map; the D2ar aquifer map of φ_{D2ar}; the map φ_{preQ} of the prequaternary surface. The distribution φ_{preQ} was prepared by the Latvian Environment, Geology and Meteorology Centre (LEGMC). The φ_{preQ} −surface can provide only fragments of ψ_{out} that can be observed from the bird's eye view. Special software was developed for extracting these data and for providing information that was necessary to design the interpolation tool that provided ψ_{out} for other aquifers. The design is based on the fact that there is a set of vertical links a_z that joins the neighbouring aquifers along the middle line of the border zone. These links account both for the k and m parameters of aquitards (2). If values of these links are considerably enlarged (at least, 1000 times), then this set of the transformed links behaves like a spatial interpolator.

Therefore, the boundary condition ψ_{out} is supported by HM itself, as follows: on the middle line of the border zone, the components ψ_{out} originated from the ψ_{rel}, φ_{D2ar}, φ_{preQ}−maps are fixed as the initial ones; the other components of ψ_{out} are provided by the set of transformed a_z−links. The interpolator is not a part of the LAMO active volume and it can be used permanently. This feature is very useful during the HM calibration when k−maps are changed and the conditions ψ_{out} follow these adjustments.

C. Rivers as Boundary Conditions

The condition ψ_{riv} that represents water levels of rivers is attached to inner nodes of the HM grid via the elements of the river bed conductance matrix G_{riv}. The flow q_{riv} caused by rivers is given by the expression:

$$q_{riv} = G_{riv} (\varphi_{riv} - \psi_{riv}) \qquad (6)$$

where the diagonal matrix G_{riv} is part of G; ψ_{riv} is the subvector of ψ, φ_{riv} represents these nodes, where the corresponding components of ψ_{riv} that represent long line profiles of rivers are attached via the links belonging to G_{riv}. Components of ψ_{riv} are fixed in nodes located outside the HM grid. The value of a single element g_{riv} of G_{riv} is presented by the formula:

$$g_{riv} = h \, w_{riv} \, k_{riv} / m_{riv} \qquad (7)$$

where h=500 (plane step); w_{riv} − the river width; k_{riv}, m_{riv} − permeability and thickness of the river bed layer, respectively; these two parametres are unknown. Value m_{riv}=1 was fixed and k_{riv}=0.02 was found experimentally. Therefore, as the initial try, the formula (7) gives g_{riv}=10w_{riv}. For LAMO, rivers are presented by their middle lines. An exception is of the Daugava River. It includes three artificial lakes of hydroelectric power plants of Riga, Kegums, Plavinas.

To obtain the ψ_{riv} −conditions (formulas (6) and (7)), the following items must be prepared: the xy−location of a river line; the long line profile (water levels ψ_{riv} of a river); the width w_{riv} of a river; the z−attachment of a river that accounts for the fact that a river, on its run, may be joined with different geological layers. For example, the Gauja River runs through the Quaternary, the upper and lower Devonian layers. It was necessary to develop special software to prepare data for the ψ_{riv}−conditions.

At present, the empirical values k_{riv} =0.02, m_{riv} =1 are applied to all rivers. In nature, k_{riv} may be different not only for each river, but also for their fragments. The elements g_{riv} can be controlled also by changing the value of m_{riv}. The task of finding more realistic g_{riv} distributions is very complex, because river flows of (6) measured in nature must be used. Knowledge of these flows will provide more exact estimates of the interaction between groundwater and rivers. The task of making use of this information is part of the LAMO future development.

IV. Creation of Z-maps

The most time-consuming part of developing LAMO was the preparation of digital z-maps that served as initial data for the GV system. For LAMO, most layers are outcropping (Fig. 4). They are not continuous, and for this reason, they do not exist everywhere.

The geometry of LAMO is based on the geological information accumulated by LEGMC. The information includes stratigraphical data of boreholes, geological maps and descriptions regarding geology of Latvia.

The LAMO geometry results in the set of z−maps. It includes 28 surfaces for 27 geological layers presented in HM (see Fig. 3). The top surface of HM (z=0) is the digital hydrogeological relief of Latvia. It includes the hydrographical network (rivers, lakes, sea). The z=1 surface is the digital geological relief. It represents the ground surface elevations. For LAMO, this map accounts for depth of the sea and of three artificial lakes of hydroelectric power plants of the Daugava River.
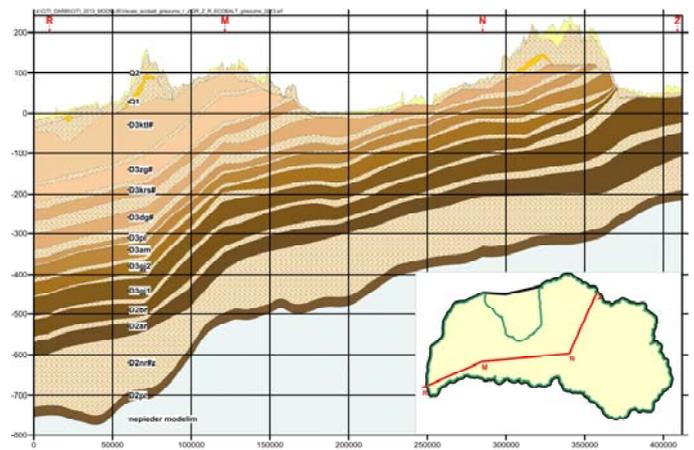

Fig. 4. Geological cross section.

The LEGMC specialists have prepared two important geological maps: the prequaternary surface preQ (z=6), the D2pr surface (z=26). They are presented in Fig. 5 and Fig. 6, respectively. The volumes of the Quaternary and primary geological layers are included between z=0, z=6 and z=6, z=27 surfaces, respectively.

The most time-consuming and difficult task [10] was the creation of z−maps for the primary geological layers (z=7, 8, …, 27). The basic stratigraphical information was carried by the boreholes and elevations of geological borderlines located on the preQ surface (Fig. 5). However, very often data of boreholes were contradictory and it was not always possible to amend them. To reduce laborious work of checking the quality of all available borehole data, the set of representing geological cross sections was used, where the chosen boreholes with trustworthy data were located. Deep boreholes were used, which provided stratigraphical data for all geological layers of HM. As a rule, data gaps occurred along a section laterally and vertically (along a borehole axis). These gaps were filled by complementary data that were concordant with the existing borehole data. The z−maps must always give positive thicknesses m. For this reason, the data of the sections must match this condition for layers of HM.

The m=0 areas of discontinuous layers also must be accounted for. It is done by using $m=\varepsilon=0.02$ instead of the zero thickness. There are three main reasons why ε must be small: geometrical distortions are minimal even if the number of overlaying m=0 areas is large (the northern part of Latvia); transmissivity $T= \varepsilon\, k$ of aquifers is small even if their k is large; conductivity g_v of aquitards $g_v=h^2 k/\varepsilon$ is great even if their k is very small.

If $\varepsilon=0.02$ then LAMO in its m=0 areas behave normally without special control measures for outcropping strata. This first stage of preparing z−maps was performed by using the EXCEL system [12].

During the second stage, the SURFER system [11] was applied to obtain a preliminary version of z−maps. The pointwise data prepared by EXCEL and data of the geological borderlines were used by SURFER.

Unfortunately, SURFER cannot provide good z−maps, because of the following reasons: only pointwise data can be processed and their number is limited; the maximum − minimum principle is not insured for output data; the condition m>0 is often violated; for the m=0 areas, the requirement ε=0.02 is neglected. However, results obtained by SURFER provided valuable information for correcting possible errors of initial data.

The final version of z−maps was obtained by the GDI system. It applied data of the representing cross sections, of the geological borderlines and of surfaces that were extracted from the preQ surface map (Fig. 5).

Geometry of buried valleys in the body of primary geological layers was not simulated by LAMO. Accounting for the buried valleys is difficult and the data about the material that fills them are uncertain.
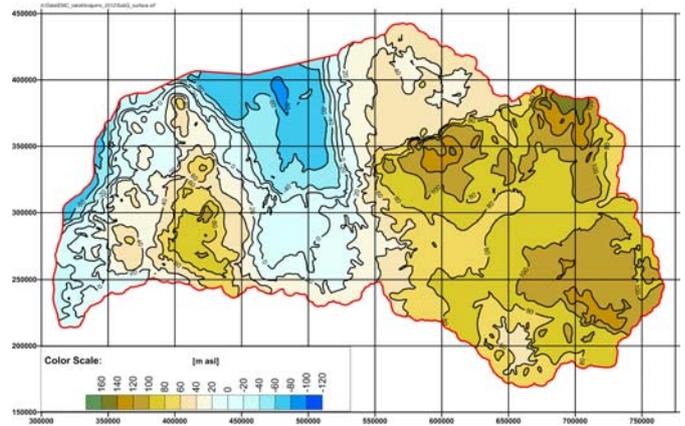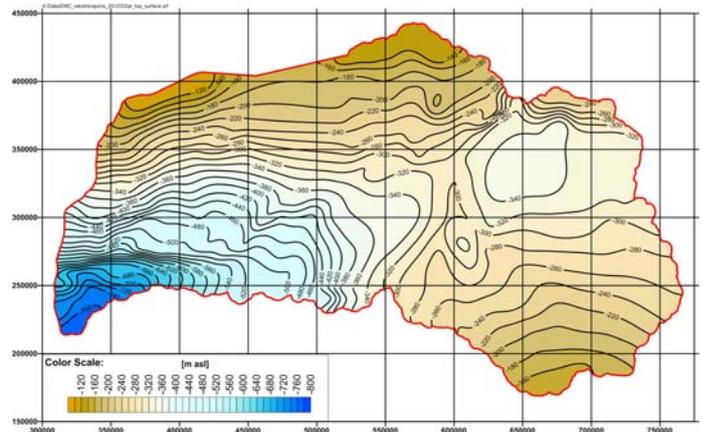

Fig. 5. The prequaternary preQ surface (z=6).

Fig. 6. The D2prn top surface (z=26).

V. CALIBRATION PROCESS

After all the necessary digital maps are 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 of (1). Calibration of HM is a controlled iterative process, involving the addition of complementary data, until 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, matrix A must incorporate the observed permeability and geometrical features of k and z−maps, etc.;
- within the HM body, groundwater flows should not reach unnatural values (infiltration flow, flows regarding the hydrological network, etc.);
- results of HM must confirm the real hydrogeological situation, because a formal agreement between the computed and observed target data does not assure correct simulation.

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

The main subjects controlled during LAMO calibration were k-maps of aquitards, because their distributions of *k* were unknown.

A valuable instrument of searching for the right k-maps was the data of vertical flows between neighbouring layers.

The flows were computed by SURFER as follows:

$$q_{i,i+1}= 0.73\times10^6(\varphi_i-\varphi_{i+1}) / (m_i / k_i+ m_{i+1} / k_{i+1}) \quad (8)$$

where $q_{i,i+1}$ was the vertical flow [mm/year] passing between the i-th and i+1-th layers. The formula holds even if both thicknesses m_i and m_{i+1} are representing ε=0.02 areas.

The k-maps have the following structure:

$$k=k_c k_{out} \quad (9)$$

where k_c and k_{out} are, respectively, the core and outer diagonal k-matrixes. The k_c matrix has no dimension and its basic value is 1.0. In the course of calibration, some k_c must be changed to values that are larger or smaller than the base value 1. The matrix k_{out} serves as the general factor for controlling the k-map for all nodes of an HM grid plane. The GDI program was used to obtain k_c–maps. The calibration of the k_{aer}–map for the aeration zone (aer) is important. Initially, its core matrix k_c values are 100.0 and 0.01 for areas of lakes and swamp areas, respectively. The following formula was used for correcting the initial k_c matrix:

$$k_c = k_c c, \quad c=1, \text{ if } \Delta \leq M \quad \text{or} \quad c=(M/\Delta)^n$$
$$\text{if } \Delta > M, \quad \Delta= \psi_{rel} -\varphi_{Q2} \quad (10)$$

where *c* is the correction matrix; the parameter *M* accounts for limitedness of the flow if $\Delta > M$ [metres].

For the areas, where $\Delta > M$, the flow q_{aer} gets limited as follows:

$$q_{aer}=k_{aer} M^n \Delta^{1-n} /0.02. \quad (11)$$

If *n*=1, q_{aer} does not depend on Δ. Then q_{aer} is controlled by the parameters k_{aer} and *M* . For LAMO, the empirical values *M*=4 and *n*=0.75were used.
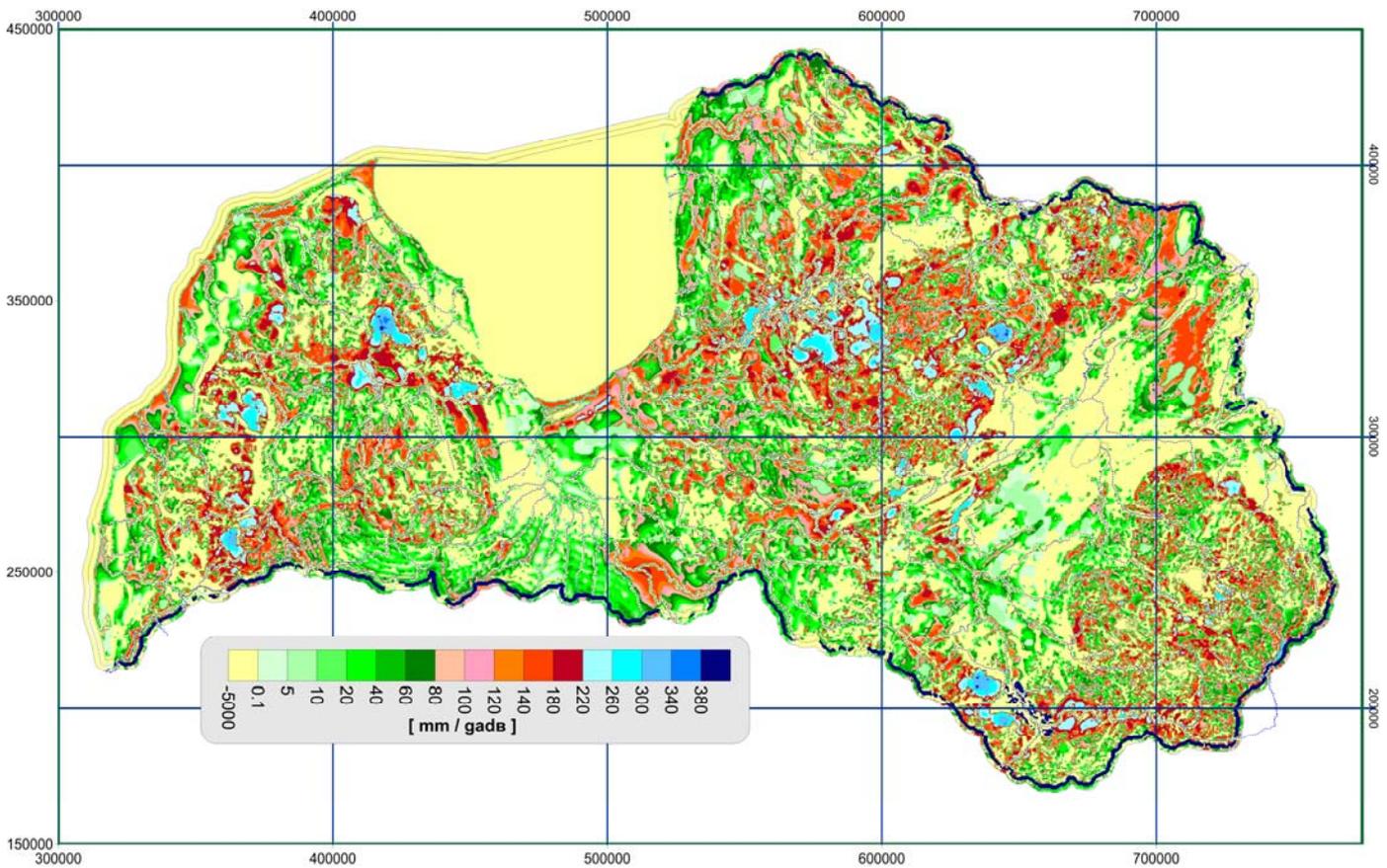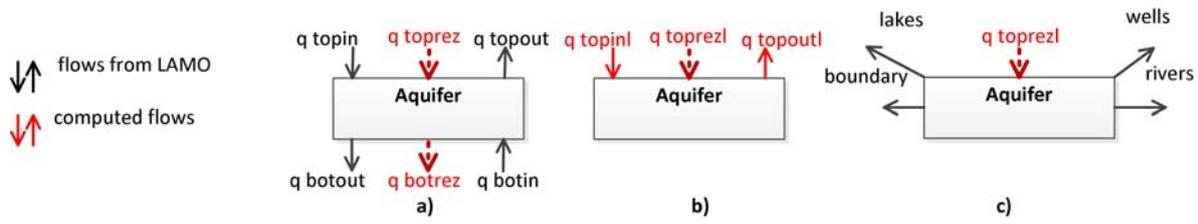

Fig. 7. Calibrated q_{aer} distribution [mm/year].

Fig. 8. Legend of stages a), b), c) for obtaining flows of Table I:
a) computing of resulting flows: q_{toprez}, q_{botrez};
b) computing of local flows q_{topinl}, $q_{topoutl}$, $q_{toprezl}$;
c) local balance of aquifer.

TABLE I

GROUNDWATER FLOWS OF AQUIFERS, THOUS.M³/DAY (PRELIMINARY VERSION)

Name of aquifer	q_{topin}	q_{topout}	q_{toprez} (2+3)	q_{botout}	q_{botin}	q_{botrez} (5+6)	q_{topinl} (2+5)	$q_{topoutl}$ (3+6)	$q_{toprezl}$ (4+7) (8+9)	rivers	lakes	boundary	i wells
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Q2	11194	-3775	7419	-6992	3461	-3531	4202	-314	3888	-3288	-426	-118	-56
Q1#	6992	-3461	3531	-6855	3349	-3506	137	-112	25	-7	0	-18	0
D3ktl#	6855	-3349	3506	-6524	3191	-3333	331	-158	173	-192	0	20	-1
D3zg#	6524	-3191	3333	-6284	3014	-3270	240	-177	63	-41	0	-18	-4
D3krs	6284	-3014	3270	-6333	2986	-3247	51	-28	23	-11	0	-8	-4
D3dg#	6233	-2986	3247	-4981	2333	-2648	1252	-653	599	-569	-10	-15	-5
D3pl	4981	-2333	2648	-3981	1849	-2132	1000	-484	516	-446	8	-70	-8
D3am	3981	-1894	2132	-3622	1634	-1988	359	-212	144	-93	0	-50	-1
D3gj2	3622	-1634	1988	-3041	1418	-1623	581	-216	365	-244	0	-96	-25
D3gj1	3041	-1418	1623	-2114	996	-1118	927	-412	505	-327	0	-154	-24
D2brt	2114	-996	1118	-852	423	-429	1262	-573	689	-462	0	-214	-13
D2ar	652	-423	429	-256	36	-220	596	-387	209	0	0	-195	-14
Model	11194	-3775	7419	-256	36	-220	10938	-3739	7199	-5680	-428	-936	-155
Q1+Q2	11194	-3775	7419	-6855	3349	-3506	4339	-426	3913	-3295	-426	-136	-56
Primary	6855	-3349	3506	-256	36	-220	6599	-3313	3286	-2385	-2	-800	-99

If $n=1$, q_{aer} does not depend on Δ. Then q_{aer} is controlled by the parameters k_{aer} and M. For LAMO, the empirical values $M=4$ and $n=0.75$ were used.

By using the rule (11), a rather smooth limitation of the infiltration flow q_{aer} was achieved for highland areas (Fig. 7). The formula (11) was used also for other aquitards of HM.

During the calibration process, the thickness $m_{aer} =0.02$ of the aeration zone is kept unchanged. As the final step, the real thickness m_{aer} must be obtained:

$$m_{aer} =0.02 \text{ if } \Delta \leq 0.02 \text{ or } m_{aer} = \Delta \text{ if } \Delta > 0.02$$
$$\Delta = \psi_{rel} - \varphi_{Q2}, \quad k_{aer} = (k_{aer})_c\, c, \quad c = m_{aer} / 0.02 \qquad (12)$$

where $(k_{aer})_c$ is the calibrated value and c is the correction matrix where its elements have values 1 and $m_{aer} / 0.02$ if $m_{ae} =0.02$ and Δ, respectively.

If for the zone aer, its real thickness m_{aer} is obtained then the thickness $(m_{Q2})_c$ decreases: $m_{Q2}=(m_{Q2})_c - m_{aer}$.

It may occur that $m_{Q2}<0$. It means that the Q2 aquifer is drained. To avoid further variations of the HM geometry (change of m for gQ2z aquitard), the assumption was made that at least 0.2 metres of the Q2 aquifer remained saturated.

This assumption holds if m_{aer} is changed as follows:

$$(m_{aer})_c = m_{aer} \text{ if } m_{Q2} >0.2 \text{ or } (m_{aer})_c = c\, m_{aer}$$

$$\text{if } m_{Q2} \leq 0.2, \quad c=(1+(m_{Q2} -0.2)/ m_{aer}); \qquad (13)$$

$$\text{when } c\, m_{aer} < 0.02 \text{ then } (m_{aer})_c = 0.02$$

where $(m_{aer})_c$ is the changed value of m_{aer}; $c\leq 1$ is the correction factor.

After dewatering of some areas for the Q2 aquifer, it was necessary to continue the calibration process, because this change of the geometry was not supported by the transformation of (12).

At present, the residual (difference between monitored and computed φ values) does not exceed 1.7 metres (a quadratic error) and 2% (a relative error).

The preliminary version of the flow distribution for LAMO aquifers is presented in Table I. The total flow of rivers q_{riv} was the calibration target. Its rough value was obtained from the book [16].

Figure 8 gives the legend of the sequential stages a), b), c) performed to obtain Table I. The stage a) represents computing of the resulting flows q_{toprez} and q_{botrez} (columns 4 and 7), respectively, on the top and bottom surfaces of an aquifer:

$$q_{toprez}=q_{topin}+q_{topout}; \quad q_{botrez}=q_{botout}+q_{botin} \quad (14)$$

where the flows q_{topin}, q_{topout}, q_{botout}, q_{botint} (columns 2, 3, 5, 6) are taken from the groundwater balance output of the GV system.

The stage b) provides local flows q_{topinl}, $q_{topoutl}$, $q_{toprezl}$ (columns 8, 9, 10):

$$q_{topinl}=q_{topin}+q_{botout}; \quad q_{topoutl}=q_{topout}+q_{botin}$$
$$q_{toprezl}=q_{topinl}+q_{topoutl}=q_{toprez}+q_{botrez} \quad (15)$$

By using expressions (15), the vertical groundwater transit flows are excluded from the aquifer balance. The flows $q_{toprezl}$, q_{river}, q_{border}, q_{wells} (columns 10, 11, 12, 13, 14) constitute local balance of the aquifer (stage c)). The flows q_{river}, q_{lakes}, q_{border}, q_{wells} are given in the GV mass balance sheet.

Comparison of the local resulting flows $q_{toprezl}$ provides clear information about the impact of each aquifer on the total balance (7199thous.m^3/day) of HM. Table I also provides summary for the Quaternary (Q1+Q2) and the primary layers: 3913thous.m^3/day and 3286thous.m^3/day, respectively.

By using data about the total infiltration, one can compute the mean infiltration [mm/year] on the land territory of Latvia (64.5thous.km^2):

$$(11194 \times 0.365)/64.5=63 \text{ [mm/year]}.$$

This recharge of groundwater resources composes 9.0% of the mean precipitation (700mm/year) for Latvia.

However, the calibration process of LAMO is not completed, because the links of the hydrographical network with the HM body have not been properly adjusted yet.

VI. CONCLUSIONS

The hydrogeological model of Latvia has been developed. To create the model, original methods have been used to obtain maps representing complex geometry of the geological environment of Latvia and to arrange various types of boundary conditions (digital relief map, conditions regarding hydrographical network, etc.). Effective methods have used to calibrate HM. The knowledge and ideas presented in this paper may be useful for modellers dealing with the problem of creating highly complex HM.

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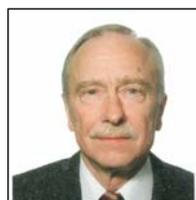
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