29th European Conference on Modelling and Simulatio

May, 26th - 29th, 2015, Albena(Varna), Bulgari

ECMS 2015

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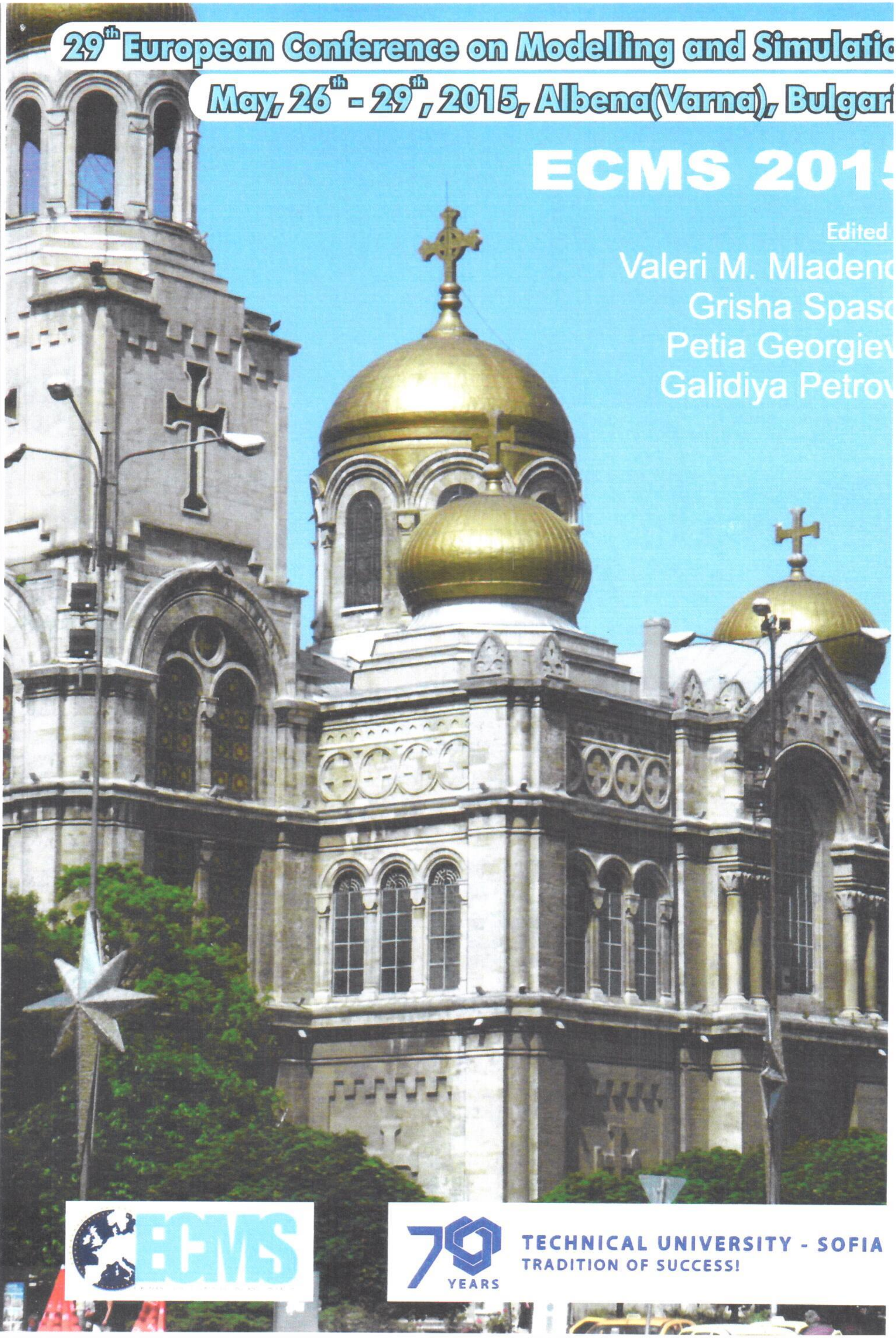

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Printed: ISBN: 978-0-9932440-0-1
CD: ISBN: 978-0-9932440-1-8

European Council for Modelling
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Cover pictures © Varna Municipality

Printed by
Digitaldruck Pirrot GmbH
66125 Sbr.-Dudweiler, Germany

Simulation of Complex Systems and Methodologies

Finance, Economics and Social Science

UPGRADING OF THE HYDROGEOLOGICAL MODEL OF LATVIA

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KEYWORDS

Regional hydrogeological model, hydrographical network, transmissivity of aquifers, geological sections

ABSTRACT

In 2010–2012, the hydrogeological model (HM) of Latvia (LAMO) was developed by scientists of Riga Technical University (RTU). The model generalizes geological and hydrogeological information accumulated by the Latvian Environment, Geology and Meteorology Center (LEGMC). LAMO simulates the active groundwater zone that provides drinking water. The worldwide used commercial program Groundwater Vistas is applied for running LAMO. In 2013 – 2014, LAMO has been considerably upgraded and, presently, three successive versions (LAMO1, LAMO2, LAMO3) can be marked. The main innovations are considered that have converted the basic LAMO1 into the more advanced LAMO3 version that accounts for larger amount of real hydrographical and geological field data.

INTRODUCTION

The European Union (EU) countries are developing HM where, by means of computer modelling, the information is obtained for water resources management that must implement the EU aims defined in (Water Framework Directive 2000). In Latvia, the LEGMC team is preparing and updating the water resources management plans for cross-border type river basins districts: those of Venta, Lielupe, Daugava and Gauja rivers.

In 2010-2012, HM LAMO has been established by scientists of RTU. LAMO simulates steady state average hydrogeological situation of Latvia. The land territory of Latvia and the area of the Gulf of Riga constitute the HM active area (Figure 1). LAMO simulates 27 geological layers (Figure 2).

The commercial program Groundwater Vistas (GV) is used for running LAMO (Environmental Simulations 2011). In (Spalvins et al. 2013), novel methods used to create LAMO have been explained and they are not described in this paper.

In 2013, by using the results of LAMO, scientists of RTU have prepared materials that are being applied by specialists of LEGMC. The main items of these materials are summarized in (Spalvins et al. 2014a).

Figure 1: Location of LAMO

Table 1: Versions of LAMO

Name of version	Year of dispose	Approximation grid			Rivers in model			Lakes
		Plane step [metre]	Number of grid planes	Number of cells [$\times 10^6$]	Number	Valleys incised	Flow data used	Number
LAMO1	2012	500	25	14.25	199	no	no	67
LAMO2	2013	500	27	15.43	199	yes	no	67
LAMO3	2014	500	27	15.43	469	yes	no	127
LAMO4	2015	250	27	61.56	469	yes	yes	127

In 2013-2014, LAMO has been considerably updated (Spalvins et al. 2014c, Spalvins and Lace 2014, Krauklis and Slangens 2014). Due to these innovations, four successive versions of LAMO can be marked (Table 1).

In 2013, (Report 2013a) was prepared that revealed necessity for urgent improvements of HM. Two upgrades were completed that changed LAMO1 into the next LAMO2 version: the number of LAMO planes was increased from 25 to 27 (see Figure 2); valleys of rivers were fully incised into the HM body;

By comparing (Report 2013a) with (Report 2013b) originated, accordingly, by LAMO1 and LAMO2 for the Gauja river basin district, one finds that results of LAMO2 are more feasible.

In 2014, LAMO2 has been turned into LAMO3: the density of hydrographical network was increased; the transmissivity for aquifers was refined.

For LAMO, the residual (difference between monitored and computed piezometric head values) does not exceed 1.7 metres (quadratic error) and 2% (relative error).

Proceedings 29th European Conference on Modelling and Simulation ©ECMS Valeri M. Mladenov, Petia Georgieva, Grisha Spasov, Galidiya Petrova (Editors)
ISBN: 978-0-9932440-0-1 / ISBN: 978-0-9932440-1-8 (CD)

No of HM plane		Name of layer	Geolo-gical 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 D3šķ 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

Figure 2:Vertical schematization of LAMO

Reliance of HM depends not only on the above reported excellent residuals, but mainly on feasible distributions of groundwater flows and their interaction with the hydrographical network. In the paper, mainly the LAMO2 and LAMO3 versions are compared, because they differ significantly in density of these networks (Table 1).

In 2015, the next LAMO4 version will appear where the plane approximation step will be 250 metres and flows of rivers will be accounted for. These upgrades will improve HM, especially, due to more accurate simulation of real interaction between groundwater bodies and surface water sources.

MATHEMATICAL FORMULATIONS

To describe upgrades of LAMO, some mathematical knowledge must be applied. By using the 3D-finite difference approximation, the x, y, z – grid of HM is built. The grid consists of $(h \times h \times m)$ sized blocks (h is the block plane step, m is the variable thickness of a geological layer). For LAMO, h=500 metres. The model constitutes a rectangular p-tiered xy-layer system where p is the number of geological layers. For LAMO, p=27 (see Figure 2). It is shown in Figure 3 that most of the layers are outcropping. After emerging at the surface, such layers have zero thickness m=0. To avoid in GV calculations "the division by zero", m=0 must replaced by small $\varepsilon > 0$ (for LAMO, $\varepsilon = 0.02$ metres).

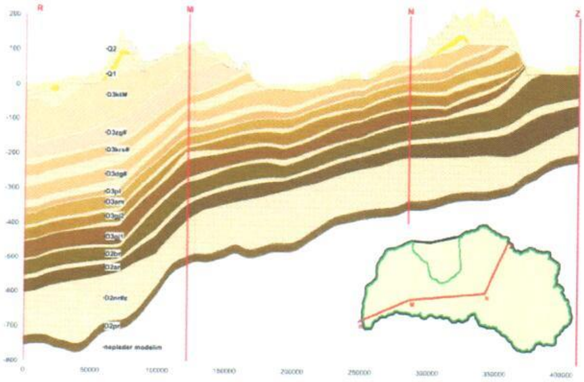


Figure 3: Geological cross section

HM provides the 3D-distribution of piezometric head vector φ as the numerical solution of the boundary field problem which is approximated in nodes of the HM xyz–grid by the following algebraic expression:

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

where A is the symmetric sparse matrix of the geological environment which is presented by the xy-layer system containing horizontal (A_{xy} – transmissivity T) and vertical (A_z – vertical hydraulic conductivity) elements of the HM grid; ψ and β the boundary head and flow vectors, respectively; G is the diagonal matrix (part of A) assembled by elements linking the nodes where φ must be found with the nodes and points where ψ is given. For LAMO, the β–flow vector is presented only by discharges of water supply wells. To support fast convergence of iterative solution process of the very large system (1), the ψ–type boundary conditions are applied on the exterior surfaces (top, bottom, sides) of the HM body. The boundary conditions ψ_{river} and ψ_{lakes}

for rivers and lakes, accordingly, also enlarge the elements of G as the diagonal dominance of A that ensures convergence of iterations (Strang, 1976).

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

$$a_{xy} = k\,m = T, \qquad a_z = h^2 k_i / (m_i + m_{i+1}\, k_i/k_{i+1}),$$
$$m_i = z_{i-1} - z_i \geq 0, \qquad i = 1, 2, \ldots, p \qquad (2)$$

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; m_i, k_i are elements of digital m_i, k_i-maps of thickness and permeability of the i-th layer, accordingly; m_{i+1}, k_{i+1} are parameters of the next underlying plane of the HM grid. The set of z-maps describes the full geometry (stratification) of LAMO.

For the i-th layer, the HM grid block centres are located on the surface $z_{i-0.5}$:

$$z_{i-0.5} = 0.5(z_{i-1} + z_i), \quad i = 1, 2, \ldots p. \qquad (3)$$

The vector φ_i and the vertical infiltration flow $\gamma_{i,i+1}$ are spatially related to this surface. The flow $\gamma_{i,i+1}$ [mm/year] can be computed by using the formula:

$$\gamma_{i,i+1} = 0.73\times10^6(\varphi_i - \varphi_{i+1})\, k_i / (m_i + m_{i+1}\, k_i / k_{i+1}) \qquad (4)$$

where the i-th and $(i+1)$-th layers are an aquitard and aquifer, respectively; the units φ [metre asl], k [metre/day], m [metre] are applied.

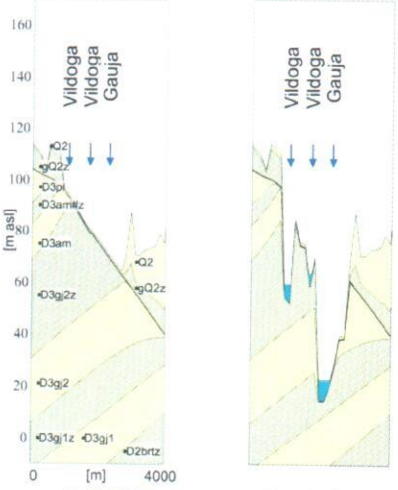
The above section contains information that is important for the HM upgrades and it does not describe the methods used for creating of LAMO.

LAMO2 UPGRADES. CROSS SECTIONS

In (Report 2013a) that was based on results of LAMO1, the customary 2D xy–distributions for heads φ_i and flows $\gamma_{i,i+1}$ appeared doubtless. However, the l,z–cross sections for these distributions (φ and γ-maps) revealed necessity for the following improvements which turned LAMO1 into LAMO2:

- the valleys of rivers should be fully incised into the HM body;
- the thick unifed D2ar# aquifer should be split into the aquifers D2brt, D2ar and the aquitard D2arz (see Figure 2, Figure 3); the number of HM layers increased from 25 to 27; the improvement was very important for the northern part of Latvia where only the D2ar# aquifer represented the active groundwater zone of the primary layers and its top reached the Quaternary strata.

The effect of the river valley incisions is explained by Figures 4a and 4b where the geological sections for the river Gauja and its tributary Vildoga are shown for the cases of LAMO1 and LAMO2. In Figure 4a, at the place of valleys the thickness of the Q2 aquifer is 1.0 metre. The thickness is 0.02 metre for fifteen layers which are present above Q2 (relh, aer) and between the Q2 and D3am layers (gQ2z, Q1#, gQ1#z, …,D3pl, D3amz).The task of arranging the z-maps even for the "incomplete" incision was complex and the effect of the full incisions of river valleys was still unknown. Therefore, only the layers Q2 and gQ2z were cut out by river valleys.



a) LAMO1 b) LAMO2

Figure 4: Incisions of valleys for the Gauja river and its tributary Vildoga

Consideration of river regimes (Report 2013a) showed that the incomplete incisions of river valleys not only distorted the ground surface geometry but also considerably crippled the river flows. It was necessary to develop more advanced software that could rearrange the z-surfaces at locations of complete incisions (Krauklis and Slangens 2014).

In Figure 4b, the full incisions of the river valleys are shown. There the geometry of the primary geological layers D3am, D3gj2z, D3gj2, D3gj1z was also changed. As an example of the φ and γ – maps, the geological cross section 4W-4E is shown (see Figure 5). There the φ – map is presented by isolines, but the γ – map is shown in the color fill mode. It is explained in (Spalvins et al. 2014b), how the φ and γ – maps are obtained. The φ and γ – isolines must be vertical within aquifers and aquitards, accordingly.

The section of Figure 5 crosses the river basin districts Venta (VN) Lielupe (LP) and Daugava (DG). Regionally, the districts VN and LP are the groundwater recharge and discharge areas, accordingly; the DG district includes both kinds of the areas. The section top is the ground surface that controls the γ–flow there. Rivers and lowlands cause groundwater discharges, but the hilly areas are the recharge sources.

The geological section map assembles the xy–type data from the $z_{i-0.5}$ planes into the lz – picture that is projected on the geological stratification formation. The map for a section provides worthy information that cannot be easily deducted from their separate xy–type data.

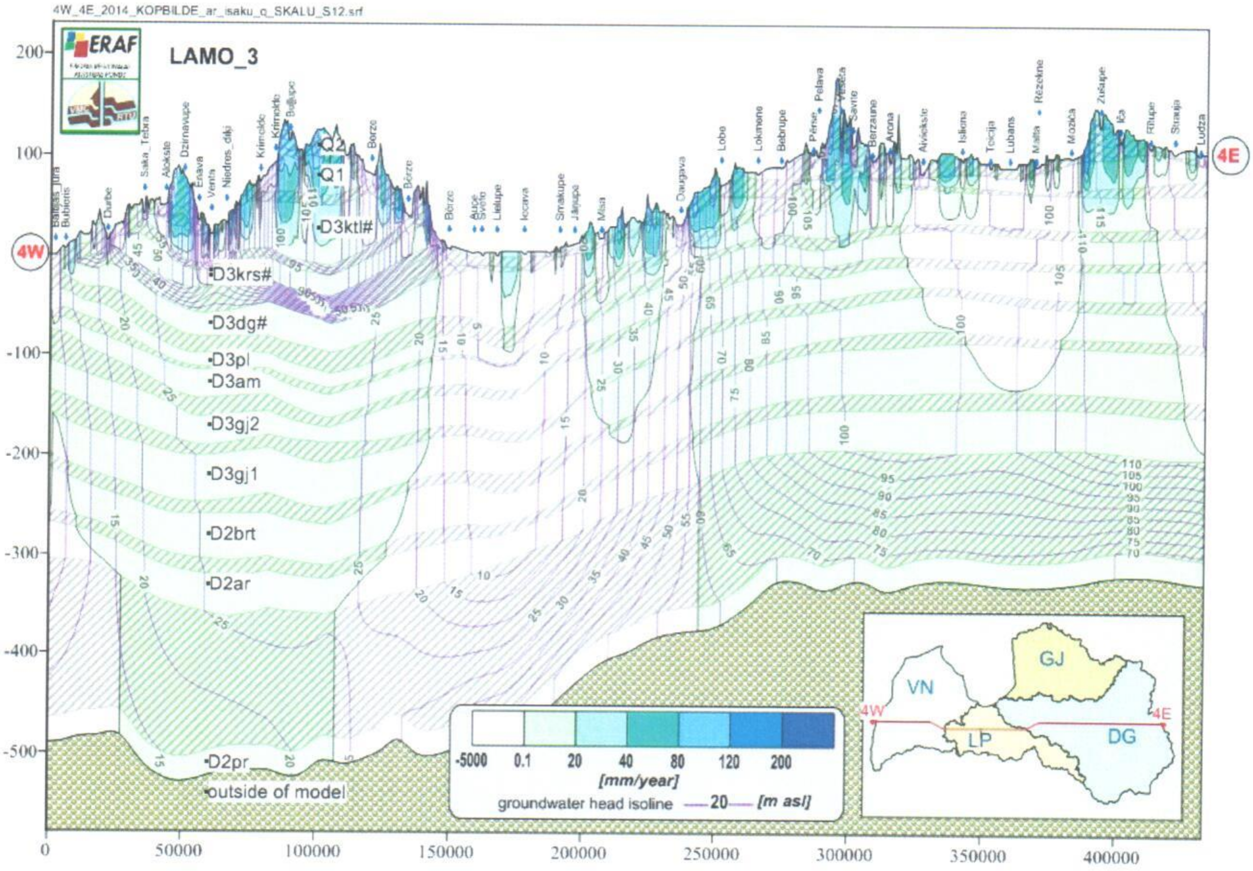


Figure 5: Geological section 4W-4E; φ and γ-maps are shown

LAMO3 UPGRADES. COMPARISON WITH LAMO2

In 2014, LAMO2 has been changed into LAMO3: the transmissivity maps of the HM primary aquifers were refined; the density for the HM hydrographical network was remarkably increased (Table 1).

As it follows from (2), the T–maps are computed by the GV system where the k and z–maps serve as the initial data. The z–maps simulate geological stratigraphy and, in fact, T can be controlled by changing only the k–maps. For LAMO, the k–map is the product:

$$k=k_{norm}\,k_{mean},\quad k_{mean}=\sum_{n=1}^{s}k_i/s\quad k_{norm}=k/k_{mean} \qquad (5)$$

where k_{norm} , k_{mean} and s, accordingly, are normalized k–maps, the mean permeability and the number of nodes within the $m > 0$ area of a geological layer; k_n is value of k for the the n-th node.

It is explained in (Spalvins and Lace 2014), how the data of well pumping have been used to obtain the k–maps for LAMO3. Table 2 provides data for the k–maps of LAMO2 and LAMO3. For LAMO2, k_{norm} =1.0, because constant values of k were used. For LAMO3, k_{norm} is variable and, in Table2, k_{norm} is the range of its matrix elements.

Table 2: k–maps for LAMO2 and LAMO3

Aquifer code	LAMO2		LAMO3	
D3ktl#	k_{norm}	k_{mean}	k_{norm}	k_{mean}
D3zg#	1.0	3.0	0.2–2.1	2.1
D3krs#	1.0	3.0	0.4–2.2	3.6
D3dg#	1.0	2.0	0.4–1.7	5.9
D3pl	1.0	10.0	0.1–1.2	5.6
D3am	1.0	10.0	0.2–1.9	7.8
D3gj2	1.0	10.0	0.3–1.8	4.7
D3gj1	1.0	10.0	0.4–1.8	5.6
D2brt	1.0	14.0	0.3–1.9	5.2
D2ar	1.0	5.0	0.3–1.8	1.9

k_{mean} [metre/day]

The effect of the variable k–maps is considered later.

To compare the groundwater flow regimes of LAMO2 and LAMO3, Table 3, Table 4, Table 5 and Table 6 were prepared. Table 3 and Table 4 contain the groundwater flow balances of Latvia that were obtained by LAMO2 and LAMO3, correspondingly.

Table 3 Groundwater flows [thous. m3/day] for LAMO2

Aquifer code	q_{inflow}	q_{rivers}	q_{lakes}	q_{border}	q_{wells}
Q2	3888	-3288	-426	-118	-56
Q1#	25	-7	0	-18	0
D3ktl#	173	-192	0	20	-1
D3zg#	63	-41	0	-18	-4
D3krs#	23	-11	0	-8	-4
D3dg#	599	-569	-10	-15	-5
D3pl	516	-446	8	-70	-8
D3am	144	-93	0	-50	-1
D3gj2	365	-244	0	-96	-25
D3gj1	505	-327	0	-154	-24
D2brt	689	-462	0	-214	-13
D2ar	209	0	0	-195	-14
Model	7199	-5680	-428	-936	-155
Q1+Q2	3913	-3295	-426	-136	-56
Primary aquifers	3286	-2385	-2	-800	-99

Table 4: Groundwater flows [thous.m3/day] for LAMO3

Aquifer code	q_{inflow}	q_{rivers}	q_{lakes}	q_{border}	q_{wells}
Q2	7223	-6596	-487	-84	-56
Q1#	47	-31	0	-16	0
D3ktl#	261	-277	0	17	-1
D3zg#	82	-64	-3	-11	-4
D3krs#	94	-80	0	-10	-4
D3dg#	800	-692	-90	-13	-5
D3pl	474	-361	-8	-97	-8
D3am	262	-237	0	-24	-1
D3gj2	527	-443	0	-59	-25
D3gj1	322	-213	-5	-80	-24
D2brt	557	-442	-6	-96	-13
D2ar	114	0	0	-100	-14
Model	10763	-9436	-599	-499	-155
Q1+Q2	7270	-6627	-487	-100	-56
Primary aquifers	3493	-2809	-112	-399	-99

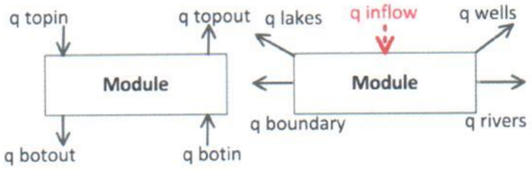
For an aquifer, GV computes the flows q_{topin}, q_{topout}, q_{botin}, q_{botout}. The sum of these flows is the inflow q_{inflow} :

$$q_{inflow} = q_{topin} + q_{topout} + q_{botin} + q_{botout} . \tag{6}$$

The inflow q_{inflow} exists only for the $m>0$ area of a layer. The GV system also finds the flows q_{river}, q_{lakes}, q_{border} and q_{wells}, accordingly, for rivers, lakes, external boundaries and exploitation wells. The sum of these flows must be in balance with q_{inflow} :

$$q_{inflow}+q_{river}+q_{lakes}+q_{border}+q_{wells}=0. \tag{7}$$

The graphical scheme for the expressions (6) and (7) is given by Figures 6a and 6b, correspondingly. There a "module" represents any part of the geological environment which flow balance is under consideration. An aquifer is the smallest module, but any HM or its parts can also be modules (Figures 7 and 8).



a) sources of inflow b) local balance

Figure 6: Scheme for explanation of flow balance

In Table 3 and Table 4, the local flow balance is given for any aquifer, for whole HM, for the Quaternary and Primary strata systems.
In Figure 7, the last three rows of Table 4 are exposed.

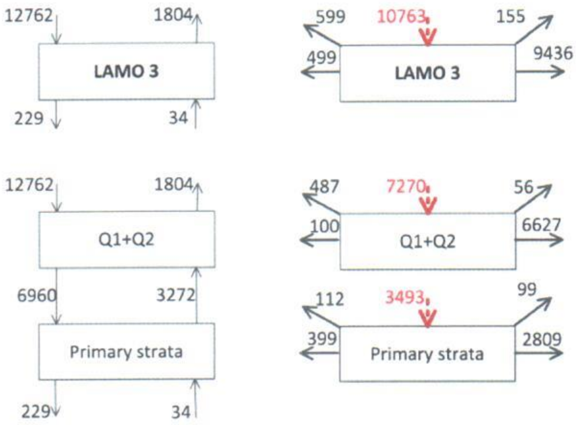


Figure 7: Mass balances [thous. m^3/day] for LAMO3

In Table 5, the difference between the flows of LAMO3 and LAMO2 are shown. The last three rows of Table 5 are shown by Figure 8.
It follows from Table 5 that the total inflow for LAMO3 was enlarged by 3564 thous.m^3/day, the flows of rivers and lakes have the enlargements 3756 thous.m^3/day and 171 thous.m^3/day, accordingly.
The LAMO2 version was calibrated to match the total river flow 6000 thous. m^3/day given in (Dzilna 1970). For LAMO3, the total river flow is much larger than for LAMO2 (9436>5680). This difference is mostly due to the Quaternary system (6627>3295), where nearly all "new rivers" of LAMO3 are joined.
Presently, it is not clear if the simulated river flows in LAMO3 are not much larger than in nature. The right answer will be possible when the measurements of river flows will be accounted for by the next LAMO4 version. The effect of the "new" lakes is little, because their areas are small (1km^2-2.5km^2). The 110 thous. m^3/day enlargement for the Primary system is caused mainly by artificial lakes of hydroelectric-power stations of the Daugava river. In LAMO3, the lakes are joined with the D3dg# and D3pl aquifers (Table 4 and Table 5).

Table 5: Groundwater flow [thous. m3/day] differences between LAMO3 and LAMO2

Aquifer code	Δq_{inflow}	Δq_{rivers}	Δq_{lakes}	Δq_{border}	Δq_{wells}
Q2	3335	-3308	-61	34	0
Q1#	22	-24	0	2	0
D3ktl#	88	-85	0	-3	0
D3zg#	19	-23	-3	7	0
D3krs	71	-69	0	-2	0
D3dg#	201	-123	-80	2	0
D3pl	-42	85	-16	-27	0
D3am	118	-144	0	26	0
D3gj2	162	-199	0	37	0
D3gj1	-183	114	-5	74	0
D2brt	-132	20	-6	118	0
D2ar	-95	0	0	95	0
Model	3564	-3756	-171	-363	0
Q1+Q2	3357	-3332	-61	36	0
Primary aquifers	207	-424	-110	327	0

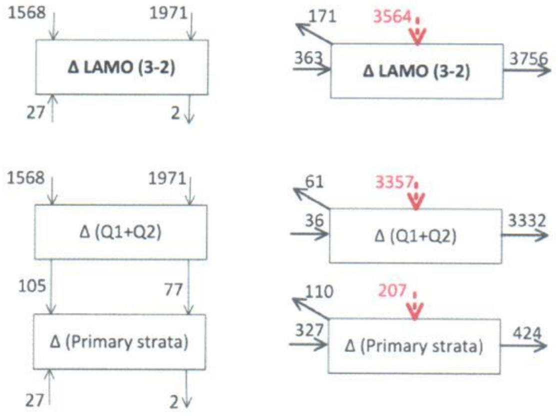


Figure 8: Flow difference [thous. m3/day] between LAMO3 and LAMO2

For LAMO3, the flow through boundaries was smaller by 363=(936–499) thous.m^3/day. This decrease was caused mainly by the Primary strata system (327 thous.m^3/day), because there for the deeper D3gj2, D3gj1, D2brt, D2ar aquifers, the k_{mean} values were smaller than the ones of LAMO2 (Table 2).

In Table 6, the infiltration flows γ [mm/year] are computed for LAMO2 and LAMO3, if the $m > 0$ areas of aquifers are accounted for:

$$\gamma = 0.365\, q_{inflow} / L \qquad (8)$$

where L [thous.km^2], q_{inflow} [thous.m^3/day], accordingly, are the area of aquifer and its inflow q_{inflow} which is taken from Tables 3 and 4.

It follows from Table 6 that for LAMO3, the mean infiltrations on the HM top and of the Quaternary system are larger (60.91> 40.73) mm/year and (41.14>22.14) mm/year, correspondingly. For the Primary strata, if their real areas are used, the flows are larger: for LAMO2 (38.63>18.59); for LAMO3 (49.90>19.76). For the Primary strata, the mean infiltration of LAMO3 is only slightly larger than one for LAMO2.

Table 6: Infiltration flow for LAMO2 and LAMO3

Aquifer code	Area [thous.km^2]	γ [mm/year]	
		LAMO2	LAMO3
D3ktl#	5.44	11.61	17.71
D3zg#	7,53	3.05	3.97
D3krs	9.34	0.90	3.67
D3dg#	32.84	6.66	8.89
D3pl	44.10	4.27	3.92
D3am	46.52	1.13	2.05
D3gj2	51.17	2.60	3.76
D3gj1	56.66	3.25	2.07
D2brt	63.40	3.96	3.20
D2ar	63.40	1.20	0.66
Primary Total	-	38.63	49.90
Model	64.50	40.73	60.91
Q1+Q2	64.50	22.14	41.14
Primary aquifers	64.50	18.59	19.76

NEXT UPGRADES

In 2015, LAMO3 will be converted into LAMO4 where the plane approximation step will be reduced from 500 metres to 250 metres. In LAMO3, bodies of rivers/lakes are somewhere touching. In LAMO4, due to use of the smaller approximation step, this problem will be eased, hence the ground surface will be simulated with the higher accuracy. Rivers will be joined with the HM body more trustworthy, because the data of the measured river flows will be accounted for.

In the near future, LAMO4 may be also used for complex geochemical studies, because the GV system can simulate migration of groundwater contaminants in space and time as described in (Mokrik et al. 2014) where HM of Lithuania has been used that is very similar with LAMO, because the RTU team has participated in its development (Spalvins et al. 2010).

CONCLUSIONS

In 2013-2014, the hydrogeological model of Latvia (LAMO) has been upgraded by scientists of Riga Technical University. The upgrades have improved credibility of the main LAMO results: the groundwater head and flow distributions, geological stratigraphy data, permeability of geological layers and etc. LAMO4 can be applied for updating information that is necessary for water management planning, as the base for creating detailed local models and for investigation of complex geochemical processes.

ACKNOWLEDGEMENTS

In 2010-2012, the hydrogeological model of Latvia LAMO has been developed within the framework of the Riga Technical University project that has been co-financed by the European Regional Development Fund. The current upgrades of LAMO are supported by the Latvian State Research program "ENVIDEnT" .

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