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This volume is issued by RTU since 1966. The volume may be of importance to specialists and students interested in computer simulation of various environmental phenomena formulated as boundary field problems.

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Hydrogeological Model of Latvia After Increasing Density of its Hydrographical Network

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Abstract **– In 2010 − 2012 the hydrogeological model (HM) of Latvia was developed and was named LAMO by scientists of Riga Technical University (RTU). The model comprises geological and hydrogeological information accumulated by the Latvian Environment, Geology and Meteorology Center (LEGMC). LAMO simulates the active groundwater zone that provides drinking water. To ensure compatibility with models of other countries, the worldwide used commercial program Groundwater Vistas (GV) is applied for running LAMO. In 2013 − 2014 LAMO was considerably upgraded and since 2012 three versions (LAMO1, LAMO2, LAMO3) of the HM have been developed. Density of the hydrogeological network was increased, transmissivity distributions for aquifers were refined and special software tools were developed to join the elements of hydrographical network (rivers, lakes, sea) with the HM body. In the paper the main innovations that have converted the LAMO2 into the next LAMO3 version are considered.**

Keywords **– Hydrogeological model, hydrographical network, transmissivity of aquifers.**

I. Introduction

The European Union (EU) countries are developing HM where by means of computer modeling the information necessary for groundwater management is obtained to implement the aims laid down by the EU Water Framework Directive [1] for sustainable use of water resources. In Latvia, the LEGMC team prepares plans for surface and groundwater management of four cross–border river basin districts: those of the Venta, Lielupe, Daugava and Gauja rivers. In 2010 – 2012 the HM LAMO was established by the scientists of RTU. The commercial program Groundwater Vistas (GV) was used for running LAMO [2]. The SURFER [3] and EXCEL [4] programs were applied to prepare the initial data for the GV system and to present the obtained results. In publications [5] - [9] novel methods and tools, used to establish LAMO, are considered.

In 2013 scientists of RTU using the results of LAMO prepared five reports [10] - [14] which were used by specialists of LEGMC for improving the management of groundwater bodies in the above mentioned four river basin districts of Latvia. The main items of the RTU reports are summarized in [15].

In 2013 – 2014 LAMO was considerably updated [16], [17] and due to the innovations four successive versions of LAMO can be distinguished. The comparison of LAMO versions is presented in the Appendix, Table 1A. In 2012 the first version, LAMO1, was established and the report [10] revealed the necessity for urgent improvements of the HM. In the first half of 2013 the following two upgrades were accomplished which converted LAMO1 into the LAMO2 version:

1. To avert unrealistic groundwater head distribution (shown for the profile 2W-2C in [10]), within the 24-th thick united aquifer D2ar#, the one was split into its natural parts: the aquifers D2brt, D2ar and the aquitard D2arz (Fig. 1) and the number of LAMO planes increased from 25 to 27;
2. River valleys were fully implemented into the HM body; for LAMO1 the valleys were immersed only into the Quaternary strata.

LAMO2 results were used to prepare the reports [11] - [14].

In 2014 LAMO 2 was turned into the LAMO3 version, due to the following upgrades:

1. The density of the hydrographical network of HM was increased (the number of rivers and lakes was changed from 199 to 469 and from 67 to 127, accordingly);
2. The transmissivity distribution for primary aquifers of HM were considerably refined [16];
3. To prepare the data for the hydrographical network special software was developed [17].

In 2014 the next LAMO4 version will appear because the following improvements of LAMO3 will be carried out:

1. The plane approximation step will be decreased from 500 meters to 250 meters;
2. To join the rivers of HM with its body more accurately, the measured flow of rivers will be accounted for;

In the paper the versions of LAMO2 and LAMO3 are compared. Due to considerable amount of complex maps and tables these materials are assembled in the Appendix.

II. Increased Density of the HM Hydrographical Network

In Fig. 1a the "old" hydrographical network of LAMO2 and the "new" rivers and lakes included in the LAMO3 are shown. Evidently, in the LAMO3 the set of 469 rivers covers the land of Latvia much more evenly than the 199 rivers of the LAMO2. In LAMO3 sixty small lakes were added.

Hence the new rivers and lakes of LAMO3 are located mostly in the aquifer Q2, the groundwater flow regime of the Q–system changed considerably (Appendix, Table 2A):

- local inflow increased from 3 313 thous.m^3/day to 7 270 thous.m^3/day;
- the flow of rivers increased from 5 680 thous.m^3/day to 9 436 thous.m^3/day;

- the outflow through the ground surface decreased from 3 775 thous.m^3/day to 1 804 thous.m^3/day;
- the flow of lakes slightly increased from 426 thous.m^3/day to 487 thous.m^3/day;
- the outflow through the border decreased from 136 thous.m^3/day to 100 thous.m^3/day.

The outflow through the ground surface was partly reduced by minimizing (by 20 times) links of rivers and lakes with the relh plane of HM (Fig. 1). The links of lakes with the HM body were decreased by 500 times. The links of rivers with the HM body were only slightly adjusted in comparison with the ones of the LAMO2 version. The influence of the $m = 0$ areas of aquitards, thickness of which is $\varepsilon = 0.02$ meter, was decreased by 10 times (for the D3akz and D3elz aquitards by 100 times) by increasing their conductivity.

The total infiltration slightly increased from 11 194 thous.m^3/day to 12 763 thous.m^3/day which was very close to the value of 13 000 thous.m^3/day given in [18].

For the LAMO3, due to increased intensity of groundwater processes for the Q–system, processes in the primary strata became slower. In Fig. 2A the distribution of groundwater flow and heads are shown for the primary aquifers of the LAMO2 and LAMO3 versions. Evidently, the LAMO3 discharge flow is smaller than the one of the LAMO2 version, but the head isoline pattern is similar in both versions. One can draw identical conclusions when observing Fig. 3a, where flow and heads of the D2ar aquifer of the LAMO2 and LAMO3 version are compared. In Fig. 2a and Fig. 3a simple color scales were applied, in order to distinguish the areas of discharge, transit and recharge flow. In Fig. 4a the LAMO3 infiltration flow for the primary and D2ar aquifers are shown where the full color scale for the infiltration flow was used.

In Fig. 5a the geological profile 4W-4E is shown for the LAMO2 and LAMO3 versions. For both HM versions the head isolines were drawn and one can conclude from comparing these profiles that the heads of the LAMO3 version are slightly lower (5 − 10 meters) than in the LAMO2. For the profile of LAMO3 the infiltration flow distribution picture was applied. In [8] the methods of creating profiles for the head and flow distributions (φ and q-maps) are explained. The isolines of heads and flow must be vertical, within aquifers and aquitards, accordingly. In Fig. 5a the SURFER color mode was used to show the flow distribution. The profile flow q–map assembles information (geological stratification, distributions of infiltration flows) carried by the vertical incision of the HM body. For example, the preQ and D2ar maps in Fig. 4a provide data, accordingly, for the top surface and the D3arz aquitard of the Fig. 5a profile. The flow profiles helped to find out and to correct some errors of HM, especially the ones related to joining rivers with the LAMO3 body.

III. Comparison of Groundwater Flow Balance of the LAMO2 and LAMO3 Versions

For the LAMO2 and LAMO3 version the flow balance of Latvia is presented in the Appendix, Table 2A. The scheme in Fig. 6a provides the graphical interpretation for the LAMO3 flow balance difference for Latvia between LAMO2 and LAMO3 version is given and the scheme in Fig. 7a explains

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

Fig. 1. Vertical schematization of LAMO.

graphically the Table 3A of the Appendix. To compare the flow balance for Latvia of LAMO2 and LAMO2 version, the scheme in Fig. 7a reflecting their difference $\Delta = q_{LAMO3}-q_{LAMO2}$ must be considered. The total local increase of LAMO3 is 3 564 thous.m^3/day. It comprises four components (3 756 for rivers, 171 for lakes, 37 for wells, –400 for border). The well flow increase is formal, because in the D3pl aquifer the drainage system rate 37 thous.m^3/day of the Riga HPS is added. The border flow decrease is considerable (936→536). The increase for the river flow for LAMO3 is caused mainly by the new rivers of the Q–system (3295→6627). It is possible that for the next LAMO4 version the river flow should be decreased.

The considerable increase of the lake flow for the primary strata (2→112) can be explained as follows:

- water reservoirs of the Riga, Kegums and Plavinu HPS are treated as lakes;
- some lakes are fully or partly linked with the primary aquifers D3zg#, D3gj1, D2brt.

In Appendix, Table 4A the relative difference $\delta = 100\,\Delta / q_{LAMO2}$ between the local balance of LAMO2 and LAMO3 is presented in the Appendix, Table 3A and Table 2A (LAMO2). The relative difference enables to ascertain changes of groundwater flow if compared with the LAMO2 flow. In the Appendix, Table 4A its content may be much larger than 100%. For example, for the lake the relative difference is ∞ if no lake is linked with the LAMO2 aquifer ($q_{LAMO2} = 0$).

When considering the local balance of the D3gj1, D2brt and D2ar aquifers one can notice that their local inflow has decreased. For this reason the river and border flow there also is smaller. This decrease may be partly caused by nearly twofold reduced permeabilities of these aquifers (Table 1) for the LAMO3 version.

IV. Refinement of Transmissivity Distribution of Aquifers

For the GV–system the transmissivity of aquifers is controlled by changing the permeability *k*–maps. The *k*–map represents the product:

$$k = k_{norm}\, k_{mean}\ , \qquad k_{norm} = k/k_{\ mean}$$

where k_{norm} and k_{mean} are accordingly normalized and denote permeabilities of a geological stratum.

It is explained in [15] how the data of well pumping were used to obtain *k*–maps for the LAMO3 version. Table 1 summarizes the results of this investigation:

- for LAMO2 $k_{norm} = 1$, because constant values of *k* are applied;
- for LAMO3 k_{norm} is variable and this feature partly causes considerable changes of the HM groundwater flow balance.

To calibrate HM, "theoretical" value k_{meant} was replaced by $k_{meanc} > k_{meant}$, because k_{meant} corresponded to the minimal transmissivity of an aquifer. It is possible to exploit the well pumping data more punctiliously by accounting for the well partial penetrating factor [15].

TABLE I

COMPARISON OF *K*–MAPS FOR LAMO2 AND LAMO3 VERSION

Aquifer	LAMO2		LAMO3		
code	k_{norm}	k_{mean}	k_{norm}	k_{meant} *	k_{meanc} *
D3ktl	1.0	3.0	0.2–2.1	2.1	3.0
D3zg#	1.0	3.0	0.4–2.2	3.6	5.0
D3krs#	1.0	2.0	0.4–1.7	5.9	6.0
D3dg#	1.0	10.0	0.1–1.2	5.6	8.0
D3pl	1.0	10.0	0.2–1.9	7.8	12.0
D3am	1.0	10.0	0.3–1.8	4.7	7.0
D3gj2	1.0	10.0	0.4–1.8	5.6	8.0
D3gj1	1.0	14.0	0.3–1.9	5.2	8/0
D2brt	1.0	5.0	0.3–1.8	1.9	3.0
D2ar	1.0	5.0	0.3–1.9	2.1	3.0

* k_{meant}, k_{meanc} theoretical and calibrated mean permeability [metre/day] for LAMO3.

V. Conclusions

In 2014 the LAMO2 version was converted into the more efficient LAMO3 version due to the appliance of denser hydrographical network of HM to the refined aquifer transmissivity distribution and to the use of special software tools. The groundwater flow balance of Latvia for both HM versions differs considerably, especially in the river flow. For the LAMO3 version, the total discharge rate of rivers is larger than the one for the LAMO2 version. The enlargement of the river flow is caused by the increase of the number of rivers simulated by HM. It is possible that the river flow enlargement must be reduced by decreasing the strength of the links that join the rivers with the HM body. More accurate links will be found for the next LAMO4 version when the measured flow in rivers will be accounted for and the HM plane step will be changed from 500 meters to 250 meters.

Acknowledgements

In 2010 − 2012 the hydrogeological model of Latvia LAMO was developed within the framework of the project "The Creating of Hydrogeological Model of Latvia to be Used for Management of Groundwater Resources and for Evaluation of Their Recovery Measures". The project has been co-financed by the European Regional Development Fund.

Appendix

Table 1A. Comparison of LAMO versions.

Fig. 1a. Hydrogeological network of LAMO2 (blue color) and the new rivers and lakes of LAMO3 (red color).

Fig. 2a. Distribution of groundwater flow and heads for primary preQ aquifers of LAMO2 and LAMO3.

Fig. 3a. Distribution of groundwater flow and heads for D2ar aquifer of LAMO2 and LAMO3.

Fig. 4a. Infiltration flow for primary (preQ) and D2ar aquifers of LAMO3.

Fig. 5a. Geological profile 4W-4E for LAMO2 and LAMO3.

Table 2a. Groundwater flow [thous.m^3/day] balance of LAMO2 and LAMO3 for Latvia (preliminary data).

Table 3a. Groundwater flow difference [thous.m^3/day] balance between LAMO2 and LAMO3 for Latvia (preliminary data).

Table 4a. Groundwater flow relative difference [%] between local balance of LAMO2 and LAMO3.

Fig. 6a. Scheme of LAMO3 groundwater flow balance of Latvia for Table 2a

Fig. 7a. Scheme of LAMO2 and LAMO3 groundwater flow difference balance for Table 3a

TABLE 1A
COMPARISON OF LAMO VERSIONS

Version	Years	Grid step [meter]	Number of layers	Number of cells×10^6	Number of rivers	Number of lakes	River valleys	River flow
LAMO1	2012	500	25	14.25	199	67	-	-
LAMO1	2013	500	27	15.43	199	67	+	-
LAMO1	2014	500	27	15.43	469	127	+	-
LAMO1	2015	250	27	61.56	469	127	+	+

Fig. 1a. Hydrogeological network of LAMO2 (blue color) and the new rivers and lakes of LAMO3 (red color).

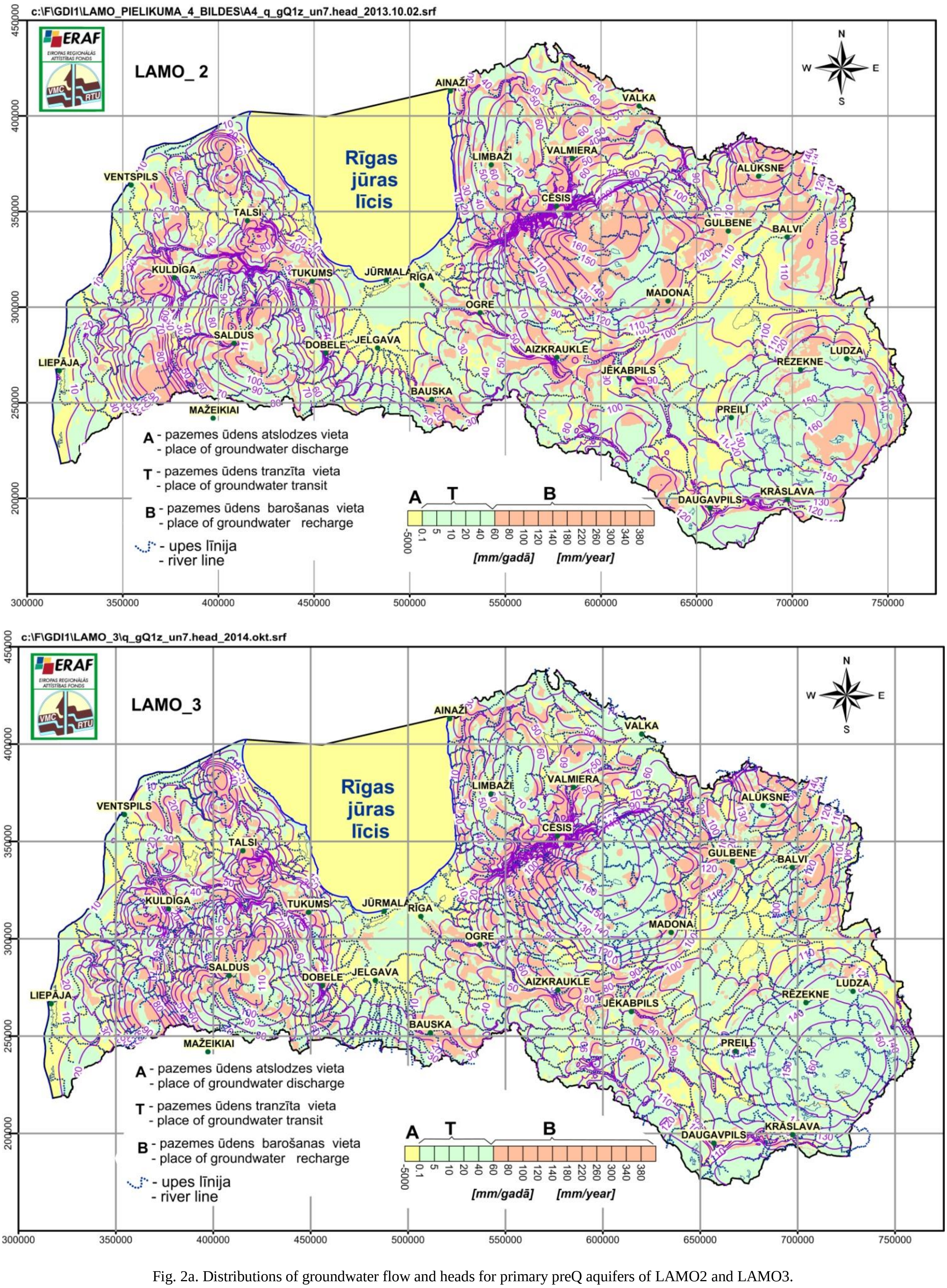
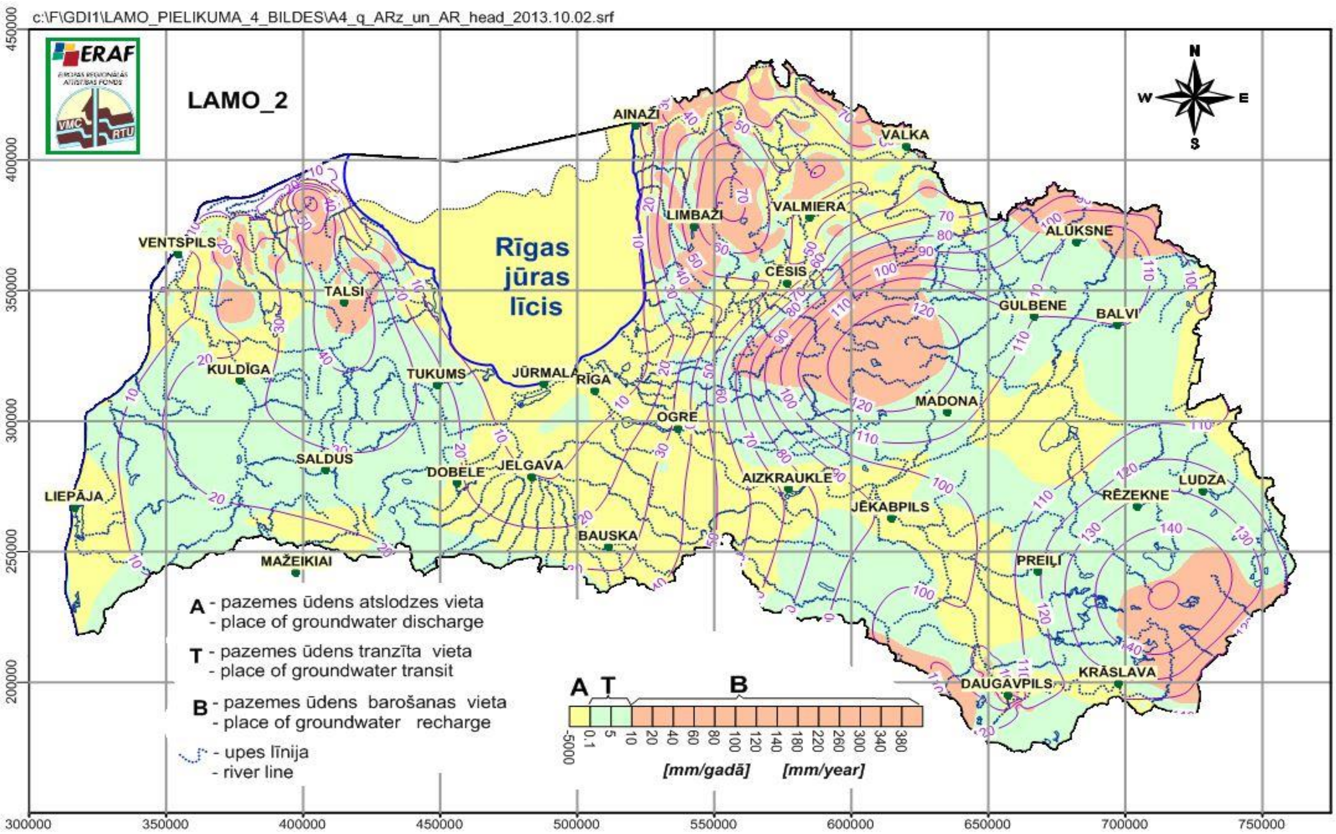


Fig. 2a. Distributions of groundwater flow and heads for primary preQ aquifers of LAMO2 and LAMO3.



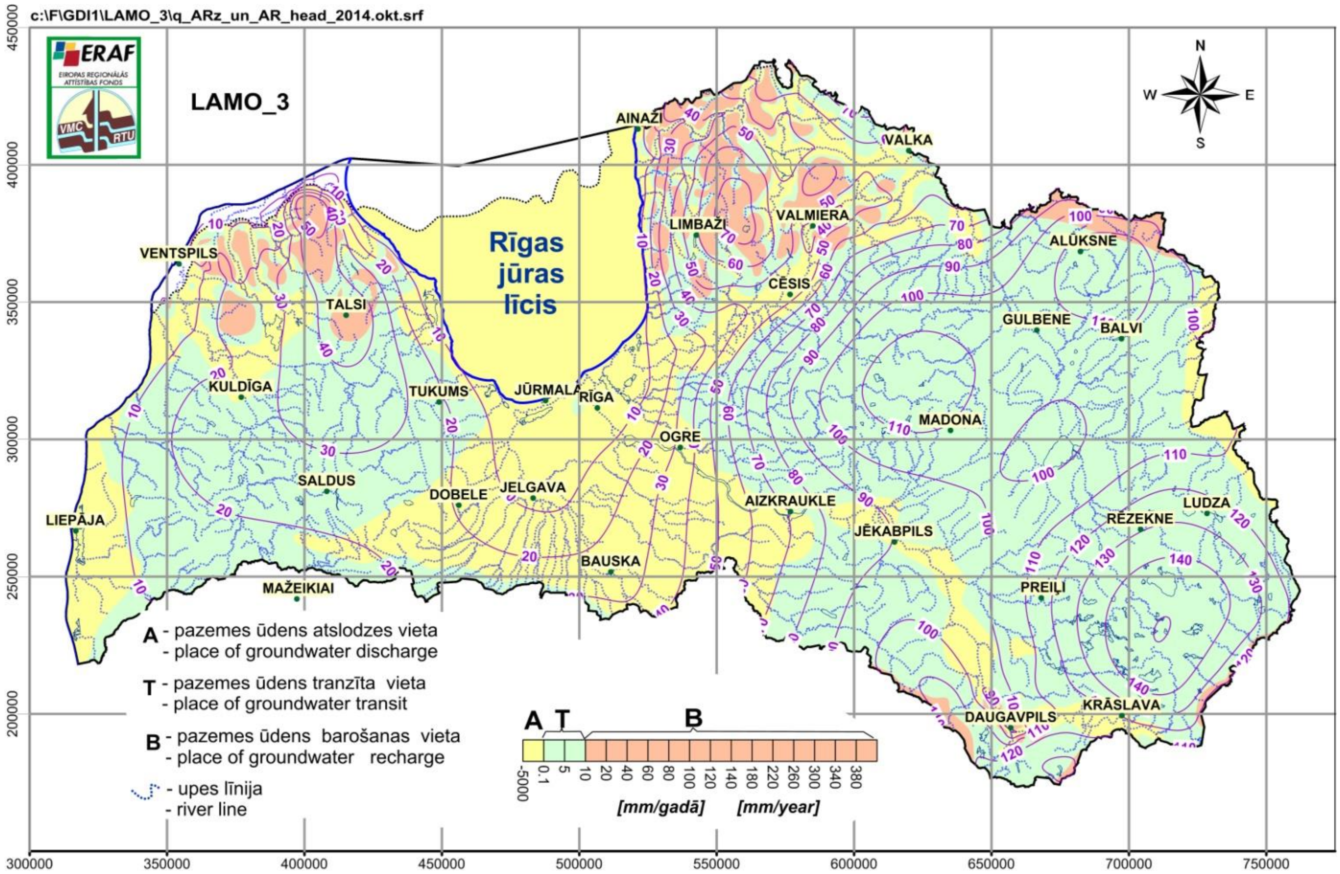
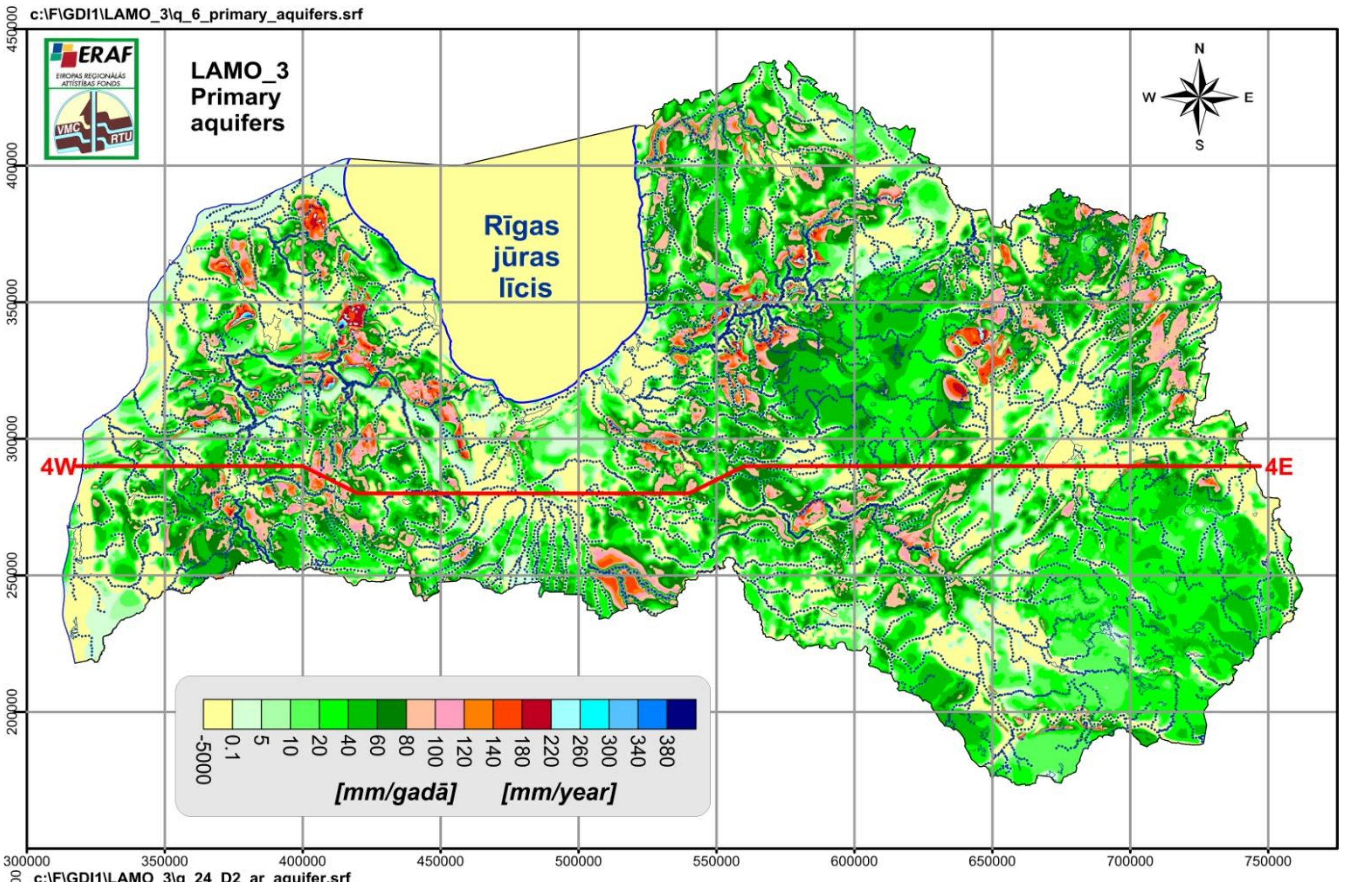


Fig. 3a. Distribution of groundwater flow and heads for D2ar aquifer of LAMO2 and LAMO3.



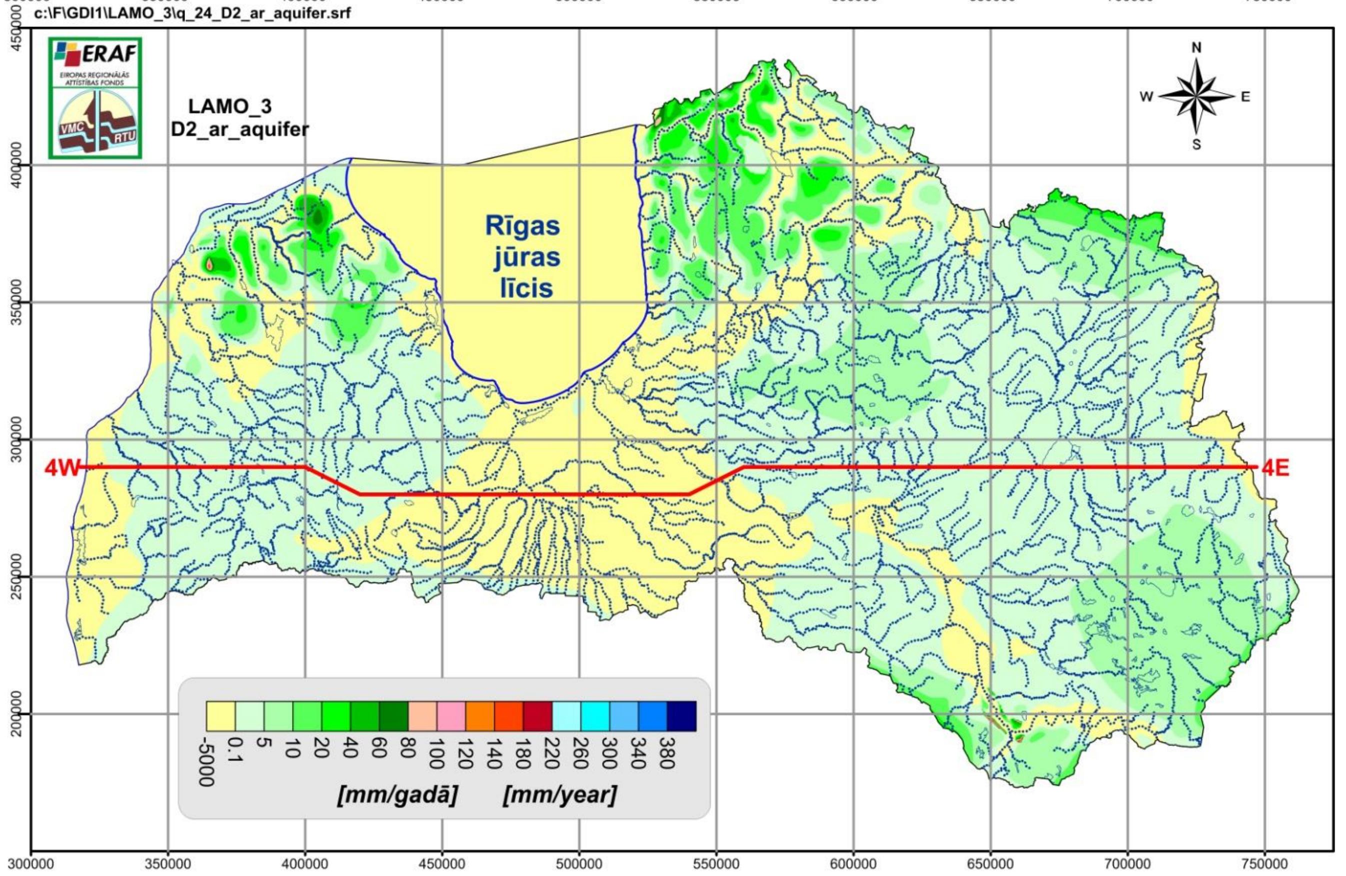


Fig. 4a. Infiltration flow for primary (preQ) and D2ar aquifers of LAMO3.

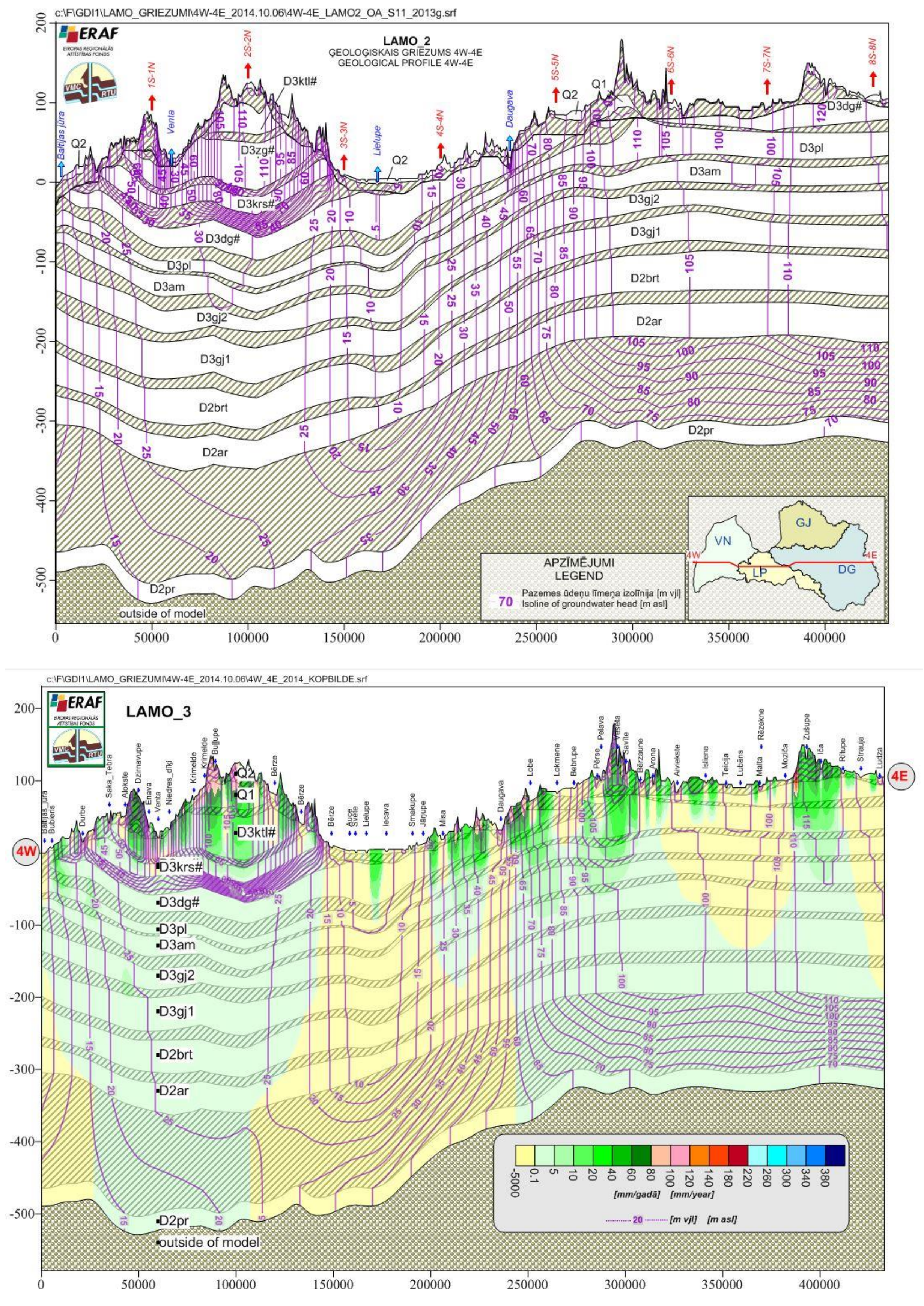


Fig. 5a. Geological profile 4W-4E for LAMO2 and LAMO3.

TABLE 2A

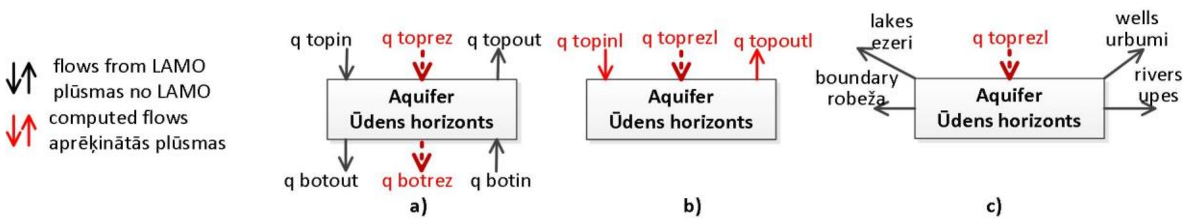
GROUNDWATER FLOW [THOUS.M^3/DAY] BALANCE OF LAMO2 AND LAMO3 FOR LATVIA (PRELIMINARY DATA)

LAMO2

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	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	-6233	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	-1849	2132	-3622	1634	-1988	359	-215	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	-422	505	-327	0	-154	-24
D2brt	2114	-996	1118	-852	423	-429	1262	-573	689	-462	0	-214	-13
D2ar	852	-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

LAMO3

Name of	q_{topin}	q_{topout}	q_{toprez}	q_{botout}	q_{botin}	q_{botrez}	q_{topinl}	$q_{topoutl}$	$q_{toprezl}$	upes	ezeri	robeža	urbumi
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Q2	12762	-1804	10958	-7125	3390	-3735	5637	1586	7223	-6596	-487	-84	-56
Q1#	7125	-3390	3735	-6960	3272	-3688	165	-118	47	-31	0	-16	0
D3ktl#	6960	-3272	3688	-6593	3166	-3427	367	-106	261	-277	0	17	-1
D3zg#	6593	-3166	3427	-6205	2860	-3345	388	-306	82	-64	-3	-11	-4
D3krs	6205	-2860	3345	-6027	2776	-3251	178	-84	94	-80	0	-10	-4
D3dg#	6027	-2776	3251	-4588	2137	-2451	1439	-639	800	-692	-90	-13	-5
D3pl	4588	-2137	2451	-3279	1302	-1977	1309	-835	474	-361	-8	-60	-45
D3am	3279	-1302	1977	-2872	1157	-1715	407	-145	262	-237	0	-24	-1
D3gj2	2872	-1157	1715	-2184	996	-1188	688	-161	527	-443	0	-59	-25
D3gj1	2184	-996	1188	-1554	688	-866	630	-308	322	-213	-5	-80	-24
D2brt	1554	-688	866	-596	287	-309	958	-401	557	-442	-6	-96	-13
D2ar	596	-287	309	-229	34	-195	367	-253	114	0	0	-100	-14
Model	12762	-1804	10958	-229	34	-195	12533	-1770	10763	-9436	-599	-536	-192
Q1+Q2	12762	-1804	10958	-6960	3272	-3688	5802	1468	7270	-6627	-487	-100	-56
Primary	6960	-3272	3688	-229	34	-195	6731	-3238	3493	-2809	-112	-436	-136



Legend of stages a), b), c) for obtaining the flow of Table 2A:

a) q_{toprez}, q_{botrez} computing of resulting flows;

b) q_{topinl}, $q_{topoutl}$, $q_{toprezl}$ computing of local flows;

c) local balance of aquifer

TABLE 3A

GROUNDWATER FLOW DIFFERENCE [THOUS.M3/DAY] BALANCE BETWEEN LAMO2 AND LAMO3 FOR LATVIA (PRELIMINARY DATA)

Name of aquifer	Δq_{topin}	Δq_{topout}	Δq_{toprez} (2+3)	Δq_{botout}	Δq_{botin}	q_{botrez} (5+6)	Δq_{topinl} (2+5)	$\Delta q_{topoutl}$ (3+6)	$\Delta q_{toprezl}$ (4+7) (8+9)	Δ rivers	Δ lakes	Δ boundary	Δ wells
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Q2	1568	1971	3539	-133	-71	-204	1435	1900	3335	3308	61	-34	0
Q1#	133	71	204	-105	-77	-182	28	-6	22	24	0	-2	0
D3ktl#	105	77	182	-69	-25	-94	36	52	88	85	0	3	0
D3zg#	69	25	94	79	-154	-75	148	-129	19	23	3	-7	0
D3krs	-79	154	75	206	-210	-4	127	-56	71	69	0	2	0
D3dg#	-206	216	4	393	-196	197	187	14	201	123	80	-2	0
D3pl	-393	196	-197	702	-547	155	309	-351	-42	-85	16	-10	37
D3am	-702	547	-155	750	-477	273	48	70	118	144	0	-26	0
D3gj2	-750	477	-273	857	-422	435	107	55	162	199	0	-37	0
D3gj1	-857	422	-435	560	-308	252	-297	114	-183	-114	5	-74	0
D2brt	-560	308	-252	256	-136	120	-304	172	-132	-20	6	-118	0
D2ar	-256	136	-120	27	-2	25	-229	134	-95	0	0	-95	0
Model	1568	1971	3539	27	-2	25	1595	1969	3564	3756	171	-400	37
Q1+Q2	1568	1971	3539	-105	-77	-182	1463	1894	3357	3332	61	-36	0
Primary	105	77	182	27	-2	25	132	75	207	424	110	-364	37

Contents of Table 3A are difference $\Delta = q_{LAMO3} - q_{LAMO2}$ between contents of Table 2a for LAMO3 and LAMO2.

TABLE 4A

GROUNDWATER FLOW RELATIVE DIFFERENCE [%] BETWEEN LOCAL BALANCES OF LAMO2 AND LAMO3

Name of aquifer	δ_{toprez}	δ_{river}	δ_{lakes}	δ_{border}	δ_{wells}
1	2	3	4	5	6
Q2	85	100	14	-29	0
Q1#	88	243	0	-10	0
D3ktl#	51	44	0	15	0
D3zg#	11	12	∞	-39	0
D3krs	308	627	0	25	0
D3dg#	33	21	800	-13	0
D3pl	-8	-19	200	-14	462
D3am	82	155	0	-52	0
D3gj2	44	81	0	-38	0
D3gj1	-36	-35	∞	-48	0
D2brt	-19	-4	∞	-55	0
D2ar	-45	0	0	-49	0
Model	2	66	40	-47	22
Q1+Q2	96	101	14	-26	0
Primary	6	18	550	-45	35

Contents of Table 4A are relative difference $\delta = 100\ \Delta/q_{LAMO2}$ that are computed as division of Table 3A / Table 2A (LAMO2)

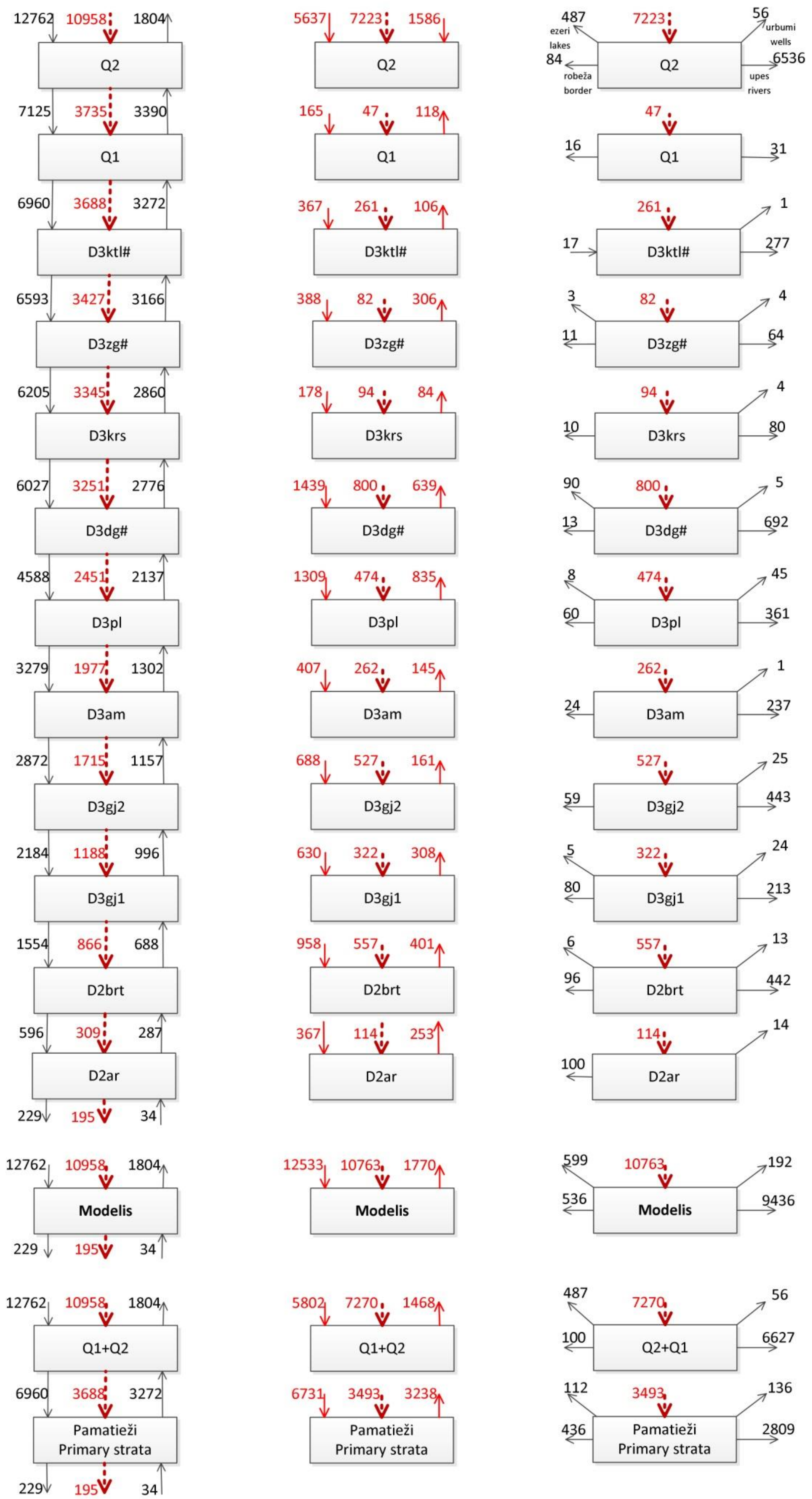


Fig. 6a. Scheme of LAMO3 groundwater flow balance of Latvia for Table 2a.

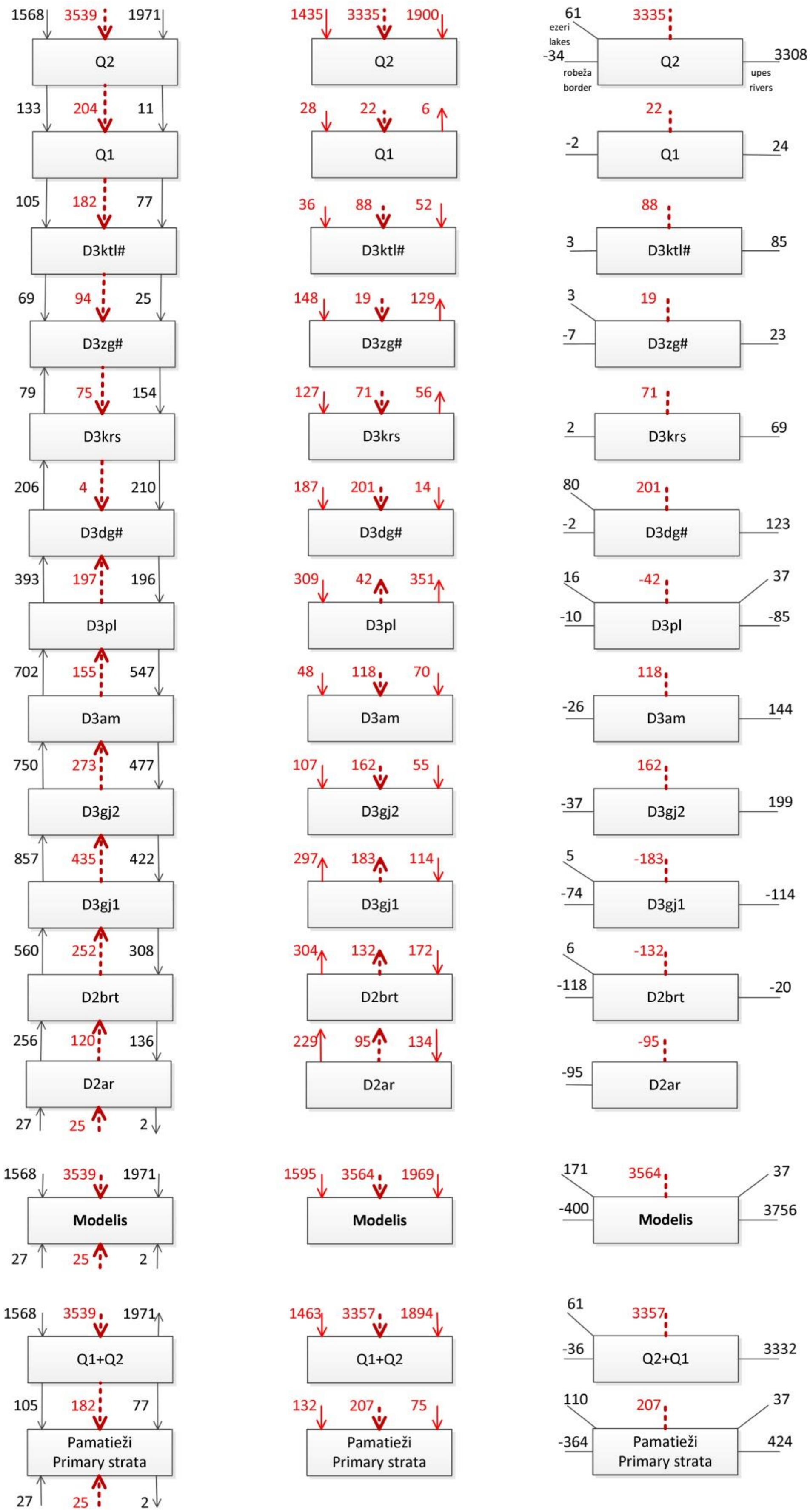


Fig. 7a. Scheme of LAMO2 and LAMO3 groundwater flow difference balance for Table 3a.

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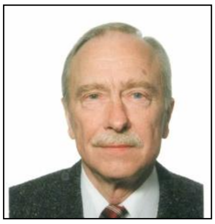

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