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Appliance of Pumping Data of Wells for Obtaining Transmissivity Distributions of Aquifers for Hydrogeological Model of Latvia

Aivars Spalvins[1], Inta Lace[2],
[1–2]*Riga Technical University*

***Abstract* – In 2010 − 2012 the hydrogeological model (HM) of Latvia called LAMO was developed by the scientists of Riga Technical University (RTU). LAMO generalizes geological and hydrogeological information accumulated by the Latvian Environment, Geology and Meteorology Centre (LVGMC). The commercial program Groundwater Vistas (GV) was used for running LAMO. In 2013 − 2014 LAMO was considerably upgraded. Density of the hydrogeological network (rivers and lakes) was increased, cuttings of river valleys into primary geological strata were accounted for, transmissivity distributions for aquifers were refined. To improve transmissivity data of HM aquifers, information provided by pumping tests for wells was used. The refined transmissivity data were applied to create the permeability maps of aquifers as the variable initial data for the GV system. To accomplish these task methods of numerical interpolation and digital image processing were used.**

***Keywords* – Hydrogeological model, numerical interpolation, pumping tests for wells, transmissivity of aquifers.**

I. Introduction

In 2010 – 2012 the HM LAMO was developed and in 2013 – 2014 it was upgraded [1] by the scientists of RTU. LAMO comprises the active groundwater zone that provides drinking water. The location of LAMO is shown in Fig. 1. As it follows from the vertical schematization of HM (Fig. 2), the current version of LAMO simulates 27 geological layers, 12 of which are aquifers. As see in Fig. 3 and Fig. 4, most of the layers are outcropping.

Fig. 1. Location of LAMO.

They are not continuous and, for this reason, they are not present everywhere in the HM area. After emerging at the surface such layers have zero thickness $m = 0$. To avoid in GV calculations “the division by zero”, $m = 0$ must be replaced by small $\varepsilon > 0$ (for LAMO, $\varepsilon = 0.02$ meters). It is explained later that the presence of the $m = 0$ areas causes problems when the permeability maps for aquifers are obtained.

To understand the aquifer transmissivity role for HM, basic mathematical expressions of numerical hydrogeological modelling [2] must be considered.

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:

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

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 and ψ and β are 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 points where ψ is given.

The transmissivity elements a_{xy}, of A_{xy}, of the HM *xy* -planes are computed, as follows:

$$a_{xy} = k_i\, m_i = T_i\,, \quad m_i = z_{i-1} – z_i\,, \;\; m_i = > 0, \quad i = 1, 2, \ldots, p \tag{2}$$

where

z_{i-1} and z_i	elevations, accordingly, of the top and bottom surfaces of the *i*-th geological layer;
p	number of surfaces (for LAMO, $p = 28$);
z_0	ground surface elevation ψ_{rel} map;
k_i , m_i	elements of the digital *km*-maps of the *i*-th layer permeability and computed thickness.

The *m*-maps are obtained from the *z*-maps and the elements T_i are also computed within the GV system [3]. For this reason, it is difficult to change the *m*-maps and one has to apply the variable permeability *k*-maps to control elements $T_i = a_{xy}$.

The matrices A_{xy} (transmissivity T) for aquifers are very important, because they control the horizontal groundwater flow regime.

For aquitards $a_{xy} \sim 0$, because their permeability k is very small and the effect of A_{xy} is insignificant.

In the Appendix, as an example, obtaining of the k-maps for the D3pl aquifer is explained.

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. 2. Vertical schematization of LAMO.

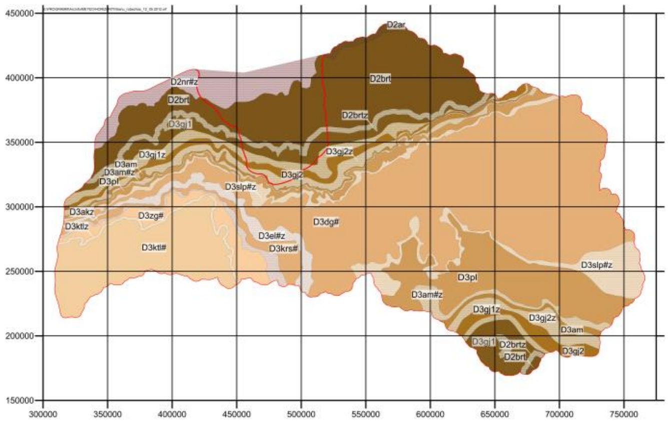

Fig. 3. Boundaries of primary geological strata.

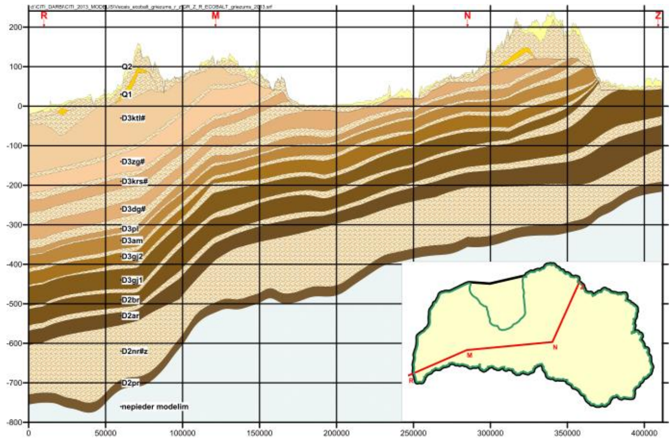

Fig. 4. Geological cross section.

II. Application of Pumping Test Results for Refining Transmissivity Data

For the well pumping test in the confined aquifer the discharge rate Q was applied and the drawdown S of the groundwater head was observed. Mathematically the test is presented by the expression [4]:

$$S = \frac{Q}{2\pi T}(\ln(R/r)+\xi)\,,\ T = km \tag{3}$$

where R are r–radiuses, accordingly, of the well depression cone and screen, ξ is additional hydraulic resistance that accounts for the partial penetrating factor of a well. From (3) one can obtain:

$$T = \frac{q}{2\pi}(\ln(R/r)+\xi)\,, \qquad q=Q/S \tag{4}$$

where q is the well specific capacity of the well.

If q and T have the dimensions, [litre/(sec.meter)], and [(meter)^2/day], respectively, then

$$T = 13.75q(\ln(R/r)+\xi)\,. \tag{5}$$

All aquifers of LAMO for the primary strata are leaky and confined. Then $R = 1.12B$ [5]:

$$B = \sqrt{\frac{km}{k_1/m_1 + k_2/m_2}} \tag{6}$$

where B is the leakage factor, $T = km$ – transmissivity of the aquifer, k_1, m_1, and k_2, m_2 are permeability and thickness of the leaky confining aquitards, accordingly, located above and below the aquifer. In Table I values of B, R and $ln(R/r)$ are given for a typical leaky confined aquifer of LAMO when $r = (0.05 – 0.1)$ meter.

TABLE I

COMPUTED VALUES OF B, R, $ln(R/r)$

km	k_1,k_2	m_1,m_2	B	R	r	$ln(R/r)$
100	10^{-4}	10	1 581	1 771	0.1	9.78
100	10^{-4}	5	2 236	2 504	0.1	10.13
100	10^{-4}	10	1 581	1 771	0.05	10.47
100	10^{-4}	5	2 230	2 504	0.05	10.82

By exploiting the fact that in Table I $ln(R/r) \sim 10$, one can approximate formula (5). If $\xi = 0$ then the following formula roughly provides the minimal value $T_{\min}$ of transmissivity for the confined aquifer:

$$T_{\min} = 137.5q\,. \tag{7}$$

In [4] the following formula is presented for computing of the resistance ξ:

$$\xi = (1/a - 1)(\ln 1.47ab - 2.65a)\,,\; a = l/m,\; b = m/r \tag{8}$$

where m is the thickness of aquifer and l and r are, accordingly, the length and radius of the well screen. The formula can be used if $m/r > 100$, $l/m \geq 0.1$. In Table II the results given by (8) are presented.

TABLE II

VALUES OF THE WELL HYDRAULIC RESISTANCE ξ

l/m	m/r			
	100	200	500	1000
0.1	21.80	28.04	36.29	42.53
0.2	11.40	14.18	17.84	20.61
0.3	6.98	8.60	10.73	12.35
0.4	4.52	5.56	6.93	7.98
0.5	2.97	3.66	4.58	5.27
0.6	1.92	2.41	3.00	3.46
0.7	1.19	1.49	1.88	2.17
0.8	0.63	0.83	1.06	1.24
0.9	0.28	0.35	0.46	0.53
1.0	0.00	0.00	0.00	0.00

If one uses the geometrical well data l/m and m/r then the resistance ξ can be applied to refine the transmissivity T, as follows:

$$T = T_{\min}(1 + \xi/10) = cT_{\min}\,. \tag{9}$$

For LAMO, the typical values of l/m and m/r are within the limits: $0.5 > l/m > 0.2$; $500 > m/r > 100$. Then, as it follows from Table II, the correction c may be within the limits: $2.78 > c > 1.29$.

III. OBTAINING OF PERMEABILITY MAPS

It was explained before that the variable permeability k-maps must be used to control the T-maps of the GV system:

$$k = T/m \tag{10}$$

where T is the transmissivity derived from the well pumping data, m is the aquifer thickness which is computed and used by the GV system to obtain $T = km$ of (2).

By using the EXCEL program [6] the set of the specific capacity q [litre/(sec.meter)] must be extracted from the well pumping data. As a rule the q-set contains very low and also very high values. In order to normalize the set, minimal and maximal values of q are fixed. The q-set contains n pointwise data. For LAMO $n > 1000$ for practically all aquifers. Due to the large n the very fast gridding method of "inverse distance to power" is applied by the SURFER program [7]. This method computes the interpolated value σ_o at the node by using the available neighboring pointwise data $\sigma_i = 137.5\, q_i$, $i = 1,\ldots, n$, as follows [8]:

$$\sigma_o = (\sum_{i=1}^{n} \sigma_i \tau_i) / \sum_{i=1}^{n} \tau_i$$

$$\tau_i = (1/d_{oi})^p\,, \qquad d_{oi} = \sqrt{(x_o - x_i)^2 + (y_0 - y_i)^2} \tag{11}$$

where τ_i weight of σ_i; d_i distance between the grid node o and the σ_i data location point; p weighting power; x_o, y_o; x_i, y_i coordinates, respectively, of the o-th grid node and the i-th point. The value $p = 2$ is used, to prepare the data for LAMO.

The interpolation result of (11) is rather rough and, to smooth it, the moving digital "inverse distance" low-pass filter of size 11×11 was used [9]:

$$\sigma_{oo} = (\sum_{i,j} \sigma_{ij} \tau_{ij}) / \sum_{i,j} \tau_{ij}\,, \quad \tau_{ij} = (1/D_{ij})^p\,, \quad D_{ij} = \sqrt{i^2 + j^2} \tag{12}$$

where τ_{ij} filter weight; p the power ($p = 0.5$ is applied); i and j the grid row and column local indices for the neighboring nodes with respect to the central node oo of the filter; D_{ij} the distance between the nodes oo and ij.

In Table III the first quadrant of the τ_{ij} matrix of the filter (12) is shown. The filter contains four symmetrical quadrants, because negative i and j indices are also applied.

TABLE III

WEIGHTS τ_{IJ} FOR THE FIRST QUADRANT OF THE 11×11 SIZE FILTER

j						
5	0.444	0.443	0.431	0.414	0.395	0.376
4	0.500	0.492	0.473	0.447	0.420	0.395
3	0.577	0.562	0.527	0.485	0.447	0.414
2	0.707	0.669	0.595	0.527	0.473	0.431
1	1.000	0.841	0.669	0.562	0.432	0.443
0	2.000	1.000	0.707	0.577	0.500	0.444
i	0	1	2	3	4	5

One can conclude from the values of τ_{ij} given in Table III that smoothing provided by the filter is rather moderate in comparison with the corresponding averaging filter ($p \rightarrow 0$) where all weight $\tau_{ij} = 1.0$. To preserve the information provided by pumping of wells, only one pass of filtering was done.

The "inverse distance" interpolation and filtering do not account for discontinuity of aquifers that include the $m = 0$ areas. Therefore, for all nodes of the 601×751 size grid of LAMO, interpolated and smoothed values of transmissivity T_{ij} are obtained. To obtain the permeability k-map from the T-grid, the formula (10) must be used where the thickness m-map is the divider. Only at the aquifer existing area where $m > 0$, reasonable values of the aquifer permeability k can arise when the operation (10) has been done. To mend the k-map produced by (10), the large values of k that are caused by the dividers $\varepsilon = 0.02$ have to be replaced by the largest value of $k_{\max}$ that can be found within $m > 0$ area of the aquifer. The final k-distributions are obtained by applying the filter of (12). For the GV system the digital k-map is presented, as the following product:

$$k = k_{\text{norm}}\, k_{\text{mean}}, \quad k_{\text{norm}} = k / k_{\text{mean}}\,, \qquad k_{\text{mean}} = \sum_{i=1}^{n} k_i / n \qquad (13)$$

where k_{norm} – normalized k–map; k_{mean} and n – the mean value of k and the number of grid nodes at the $m > 0$ area, accordingly.

TABLE IV

SUMMARY OF CHARACTERISTIC PARAMETERS OF THE PRIMARY AQUIFERS OF LAMO

C	L_C	m_{mean}	k_{mean}	$k_{\min}$	$k_{\max}$	$T_{\min}$	$T_{\max}$	$(l/m)_{\text{mean}}$
D3ktl	5.44	62.89	2.12	0.5	4.5	82.66	214	0.15
D3zg	7.53	50.43	3.64	1.5	8.0	125.38	330	0.24
D3krs	9.34	22.71	5.95	2.3	10.0	121.17	263	0.36
D3dg	32.84	30.76	5.58	0.7	10.0	127.82	474	0.34
D3pl	44.10	22.98	6.11	1.3	20.0	146.9	513	0.55
D3am	46.52	22.11	4.69	1.5	8.5	94.87	212	0.53
D3gj2	51.17	26.55	5.58	2.2	10.0	136.00	282	0.49
D3gj1	56.66	31.79	5.24	1.6	10	145.62	244	0.51
D2brt	68.96	45.30	1.91	0.6	3.5	79.02	129	0.40
D2ar	68.96	41.00	2.13	0.65	4.0	80.64	133	0.50

In Table IV the summary of characteristic parameters for the primary aquifers of LAMO are presented. The data for the k and T values are preliminary, because they have been obtained due to rather rough approximations without accounting for the hydraulic resistances of individual wells. No checking of pumping data correctness has been done.

In Table IV the following acronyms are used: C is the code of aquifer; L_C is the area of aquifer [thous.km^2]; m_{mean} is the mean thickness [meter]; k_{mean}, $k_{\min}$, $k_{\max}$ are mean, minimal, maximal permeability [meter/day]; T_{mean}, $T_{\max}$ are mean, maximal transmissivity [(metre)^2/day]; (l/m) is mean parameter that can be used to compute the resistance ξ that is applied for the correction (9).

IV. CONCLUSION

Formerly, the constant values represented the permeability k-maps of LAMO. By using the information of well pumping, the upgraded variable k-maps have been created. To obtain them, the digital interpolation and image processing methods were applied. Currently the new k-maps are used in LAMO that results in refined transmissivity distributions of the HM primary aquifers. To make these results better the well geometrical data will be accounted for and the initial pumping data will be checked and corrected.

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APPENDIX

APPLICATION OF WELL PUMPING DATA FOR CREATING OF THE D3PL AQUIFER *K*-MAP.

In Fig. 1a the location of wells is shown. They are not distributed evenly within the area of aquifer. Number of wells $n = 1730$; $5.0 > q > 0.3$.

In Fig. 2a the interpolated and smoothed isolines of transmissivity are shown when the "inverse distance" method (11) and the filtering (12) have been applied. The results are existing in all nodes of the full LAMO area grid.

The m-map of the aquifer thickness is shown in Fig. 3a. One can notice that the map includes rather deep incisions of the Daugava and Saka river valleys.

In Fig. 4a the initial and filtered k-maps are shown. Filtering has eliminated the wrong uplift of the k values at the places of incisions of the Daugava and Saka river valleys.

Formerly the k-map for the D3pl aquifer was a constant value. The upgraded k-distributions of Fig. 4a are rather variable and, for this reason, the parameter k_{mean} is used as a part of the product (13) for the GV system.

The final refined T-map which is currently used by LAMO is shown in Fig. 5a. Due to filtering of the k-map at the location of incisions of the Daugava and Saka river valleys the transmissivity is correct.

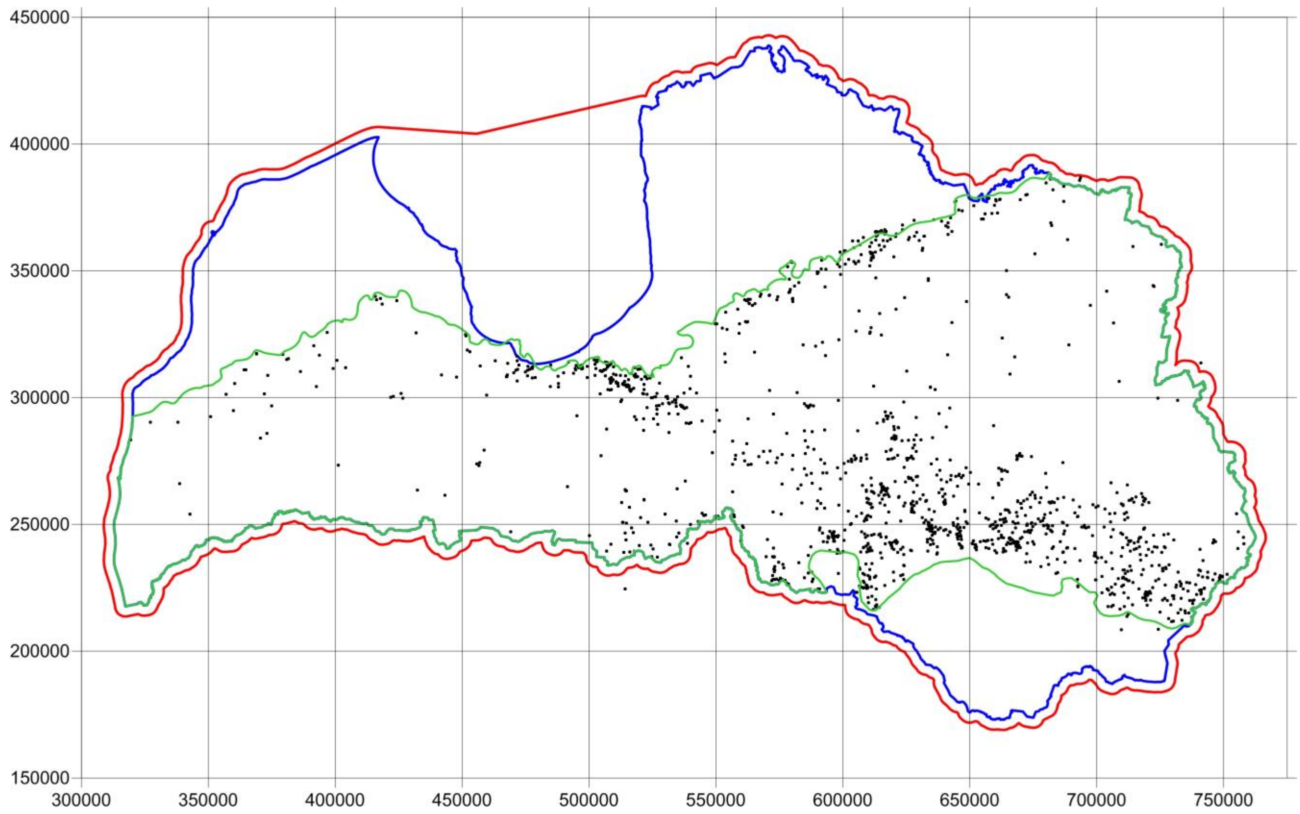

Fig. 1a. Location of wells for the D3pl aquifer.

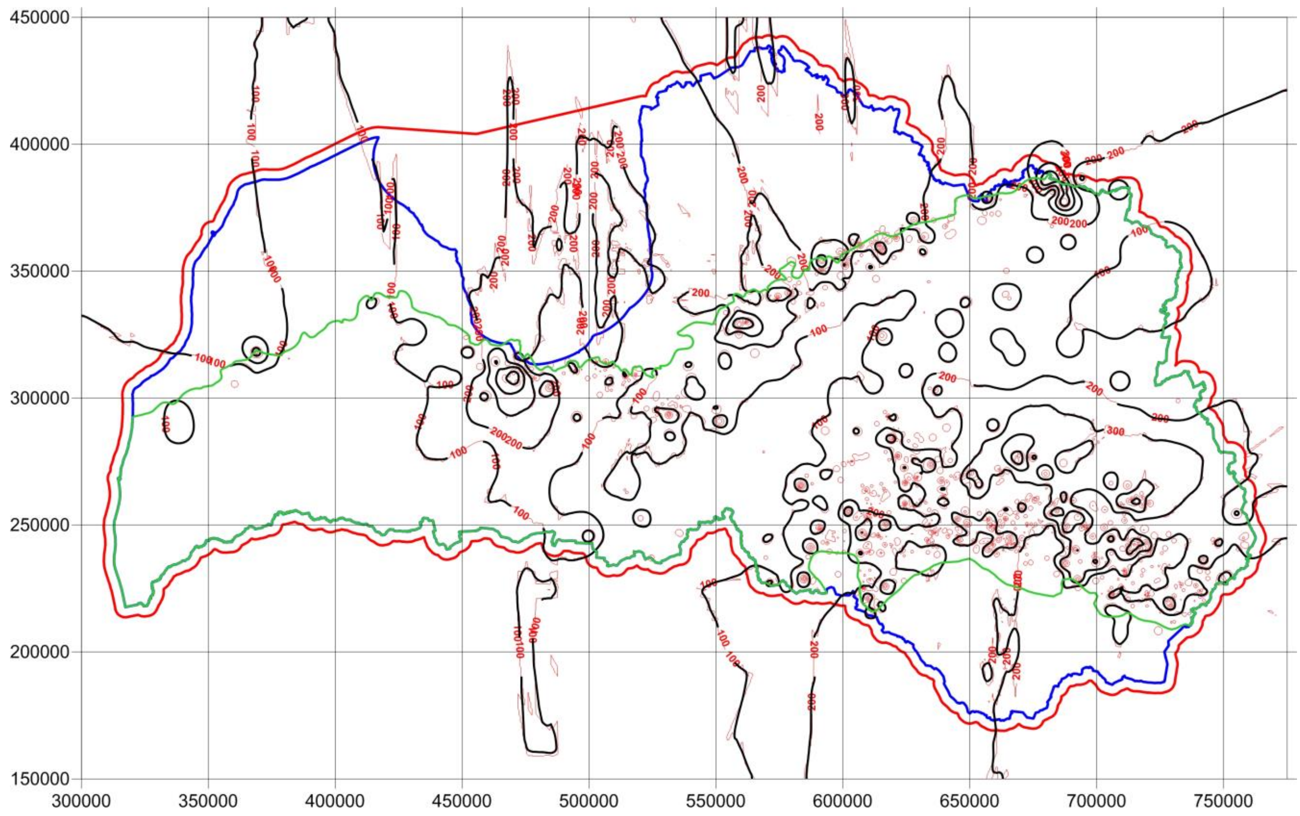

Fig. 2a. Interpolated (red) and smoothed (black) isolines of transmissivity.

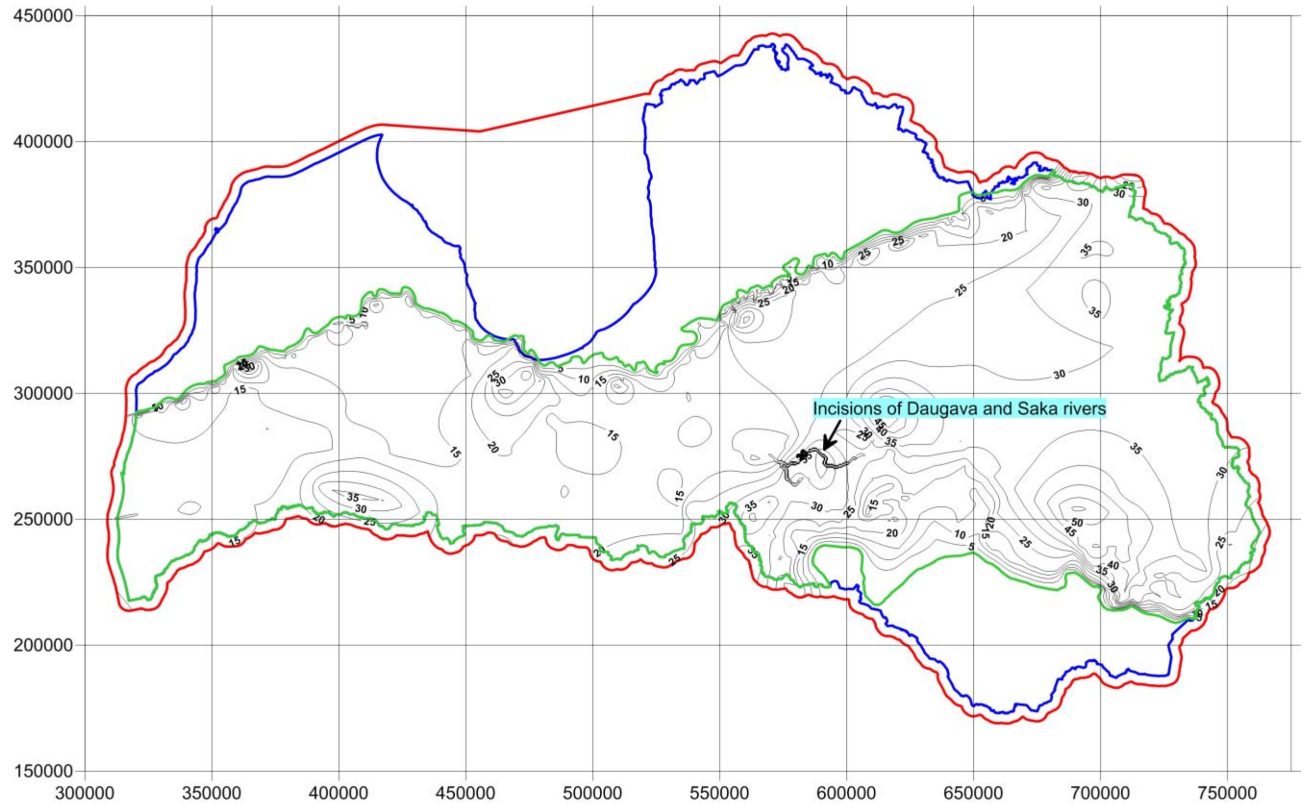

Fig. 3a. *M*-map for the aquifer thickness; incisions of the Daugava and Saka river valleys.

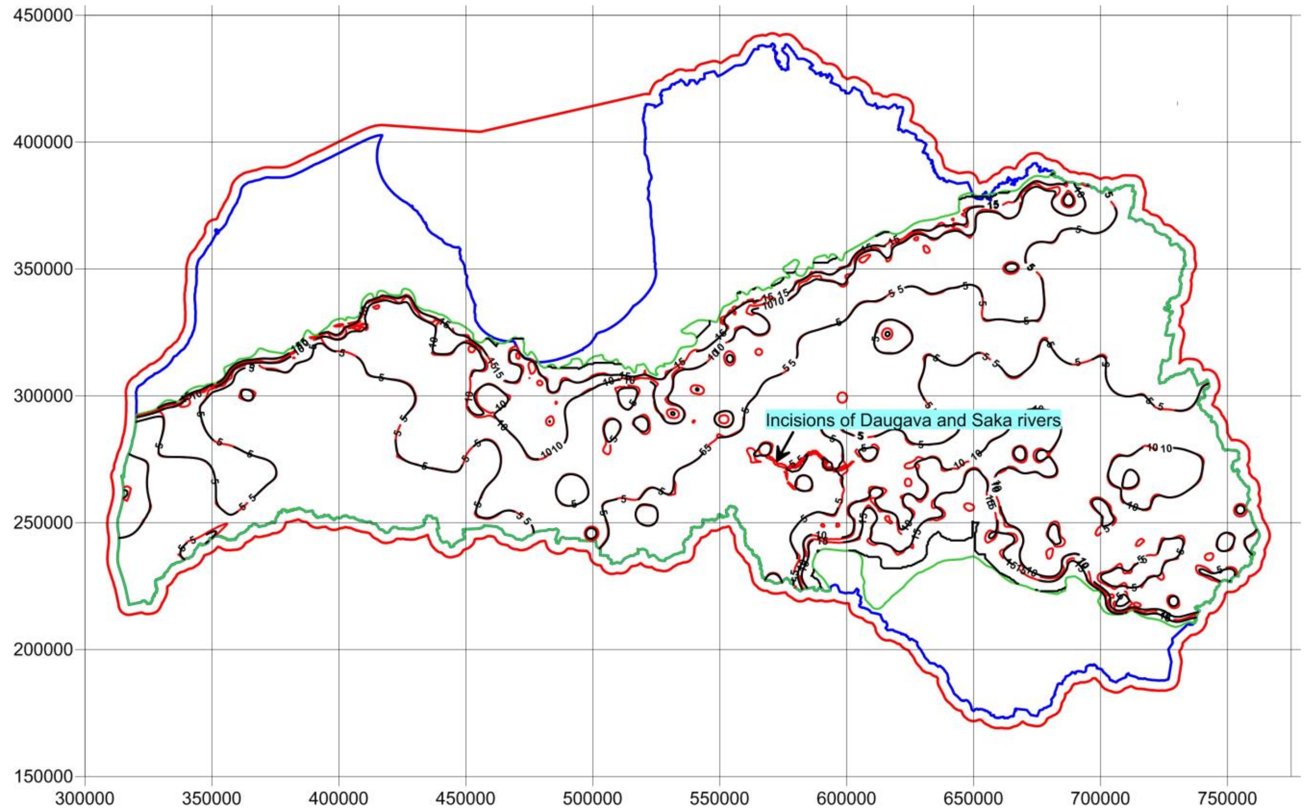

Fig. 4a. Initial and filtered *k*-maps (initial and filtered lines are red and black); filtering has eliminated the wrong uplift of the *k* values at the places of incisions of the Daugava and Saka river.

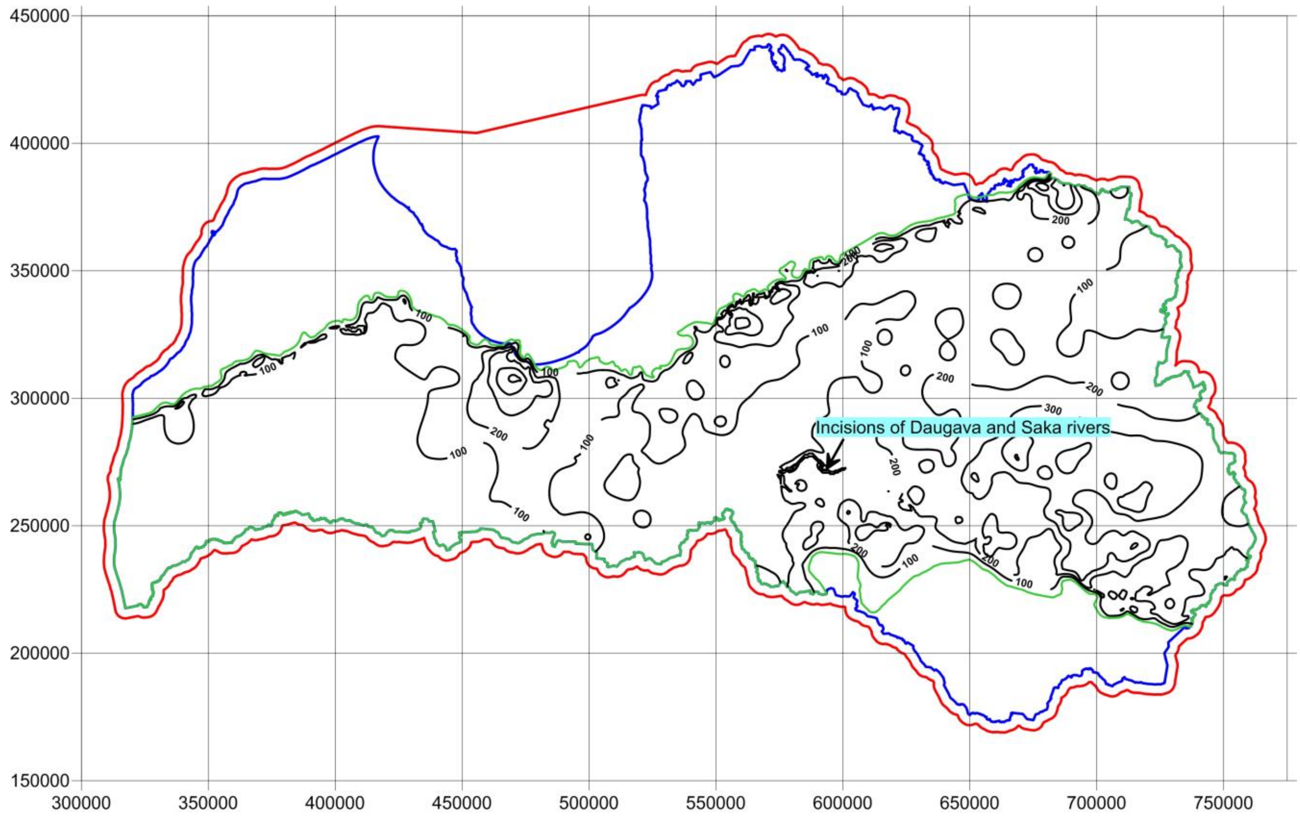

Fig. 5a. Final *T*-map. Places of the Daugava and Saka river incisions and transmissivity drops.

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Aivars Spalvins was born in Latvia. In 1963, he graduated from Riga Polytechnical Institute (Riga Technical University since 1990) as a Computer Engineer. He is currently Head of the Environment Modelling Center of RTU. His research interests include computer modelling of groundwater flows and migration of contaminants.

E-mail: emc@cs.rtu.lv

Inta Lace was born in Latvia. In 1971, she graduated from Riga Polytechnical Institute (Riga Technical University since 1990) as a Computer Engineer. In 1995, she received the Master's degree in Applied Computer Science. Since 1991, she is a Researcher with the Environment Modelling Center, Faculty of Computer Science and Information Technology, RTU.

E-mail: emc@cs.rtu.lv