Improved Methods for Obtaining Permeability Maps of Aquifers for the Hydrogeological Model of Latvia

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***Abstract* – In 2010–2012, the hydrogeological model (HM) of Latvia (LAMO) was developed by the scientists of Riga Technical University (RTU). LAMO comprises geological and hydrogeological data provided by the Latvian Environment, Geology and Meteorology Centre (LEGMC) for the active groundwater zone of Latvia. In 2013–2015, LAMO was notably upgraded. The number of HM layers and the density of hydrographical network (rivers, lakes) were increased, cuttings of river valleys into primary geological layers were done, plane approximation step was reduced twofold, transmissivity distributions of aquifers were refined by creating variable permeability maps. In the paper, new methods are described for obtaining more reliable permeability maps by using pumping data of wells. Computer-based checking of initial data for wells was accomplished, and some drawbacks of the former maps were eliminated.**

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

I. INTRODUCTION

In 2010–2012, the HM LAMO was established by the scientists of RTU. The commercial program Groundwater Vistas (GV) is used for running LAMO [1]. In 2013–2015, LAMO was considerably upgraded [2]. Due to these upgrades, four versions of LAMO can be marked (see Table I).

LAMO comprises the active groundwater zone of Latvia that provides drinking water. In Fig. 1, the location of LAMO is shown. The current version of LAMO simulates 27 geological layers (see Fig. 2). It is shown in Fig. 3 that most of them are outcropping. After emerging at the surface, such layers have zero thickness ($m = 0$).

Fig. 1. Location of LAMO.

Presence of the $m = 0$ areas and cuttings of river valleys in the thickness maps (m-maps) of GV caused problems when the permeability maps (k-maps) for aquifers were obtained by using the pumping data of wells [3].

To understand the aquifer transmissivity importance for HM, the basic mathematics for HM must be considered.

Vector φ of the piezometric head is the numerical solution of the boundary field problem which is approximated in the nodes of the HM xyz-grid by the following algebraic expression [2]:

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

where A is the hydraulic conductivity 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 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 locations where ψ is given.

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

$$a_{xy} = k_i\, m_i = T_i\,, \quad m_i = z_{i-1} - z_i\,, \quad m_i = > 0,\ i = 1, 2,\ \dots, p,\ (2)$$

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

The m-maps are obtained by GV from the z-maps, and the maps of T_i are computed within the GV system [1]. For this reason, one has to apply the variable permeability k-maps to control $T_i = a_{xy}$, because the z-maps that are used for creating m-maps cannot be changed easily.

TABLE I
VERSIONS OF LAMO

Name of version	Year of disposal	Approximation grid			Rivers in the model			Lakes
		Plane step, meters	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

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. 2. Vertical schematization of LAMO.

It was shown in [3], how the variable *k*-maps were obtained for the HM version LAMO3 by using the pumping data of wells. In the paper, new methods that have been used for creating more reliable *k*-maps for the current LAMO4 version are described.
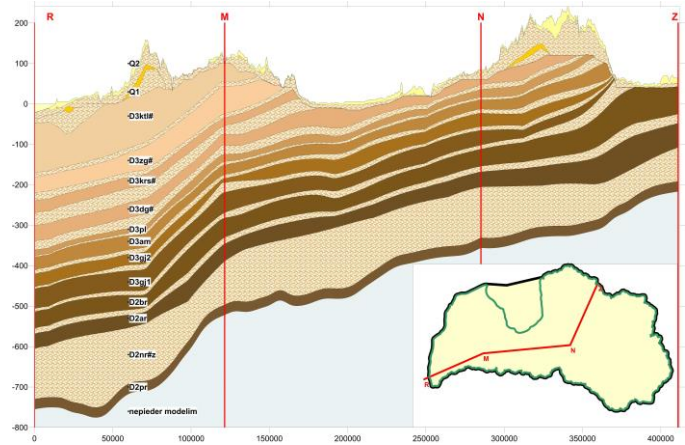

Fig. 3. Geological cross section.

II. APPLICATION OF PUMPING TEST RESULTS FOR REFINING TRANSMISSIVITY MAPS FOR AQUIFERS

A pumping test of a single well in a confined aquifer uses the discharge rate *Q*. The drawdown *S* of the groundwater head is observed which value is given by the expression [4]:

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

where *R* and *r* are radiuses, accordingly, of the well depression cone and the screen; ξ and γ are dimensionless hydraulic resistances that account for the partial penetrating factor of a well and for the quality of the well screen, respectively. For a new well, $\gamma = 0$. For old wells, the screen resistance γ increases; its value is unknown, and, for this reason, only pumping data of the new wells can provide credible results. Thus, $\gamma = 0$ should be used in (3).

From (3), the following expression can be obtained:

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

where *q* is the specific capacity of a well.

If *q* and *T* have the dimensions, liter/(sec.meter) and (meter)^2/day, respectively, then

$$T = 13.75q(\ln(R/r) + \xi). \qquad (5)$$

It was shown in [3] that for the leaky confined primary aquifers of LAMO, $ln(R/r) \sim 10.0$. If $\xi = 0$, then (5) is roughly approximated by the following expression:

$$T_{min} = 137q. \qquad (6)$$

In [5], the formula is given for computing of ξ:

$$\xi = (1/a - 1)(\ln 1.47ab - 2.65a), \ a = l/m, \ b = m/r, \qquad (7)$$

where *m* is the thickness of an aquifer, and *l* and *r* are, accordingly, the length and radius of the well screen. The formula can be used if $m/r > 100$, $l/m \geq 0.1$.

The resistance ξ can be applied to refine the transmissivity T, as follows:

$$T = v\,T_{min} \ , \quad v = 1 + \xi / 10.0 \ . \tag{8}$$

For LAMO, the typical values of l/m and m/r are within the limits: $0.5 > l/m > 0.2$ (Table III); $500 > m/r > 100$. Then, as it follows from (7) and (8), the correction factor v may be within the limits: $2.8 > v > 1.3$ [3].

Presently, the resistance ξ is not accounted for. However, the expression (8) shows that a modeler can use $T > T_{min}$, if necessary.

III. OBTAINING OF PERMEABILITY MAPS

The k-maps of permeability must be used to control the T-maps of the GV system:

$$k = T/m, \tag{9}$$

where the transmissivity T is derived from the well pumping data; m is the aquifer thickness which is used in (2) by the GV system.

By using the EXCEL program [6], the set of the specific capacity q, liter/(sec.meter), must be extracted from the well pumping data. As a rule, the q-set contains very low and also very high improbable values. In order to normalize the set, minimal and maximal values of q are fixed (for LAMO3, $q_{min} = 0.3$ and $q_{max} = 5$). The q-set contains n pointwise data. For LAMO, $n > 1000$ for practically all aquifers. Due to the large n, the 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 grid nodes by using the available pointwise data $\sigma_i = 137 q_i$, $i = 1,\ldots,n$, as follows [8]:

$$\sigma_o = (\sum_{i=1}^{n} \sigma_i \tau_i) / \sum_{i=1}^{n} \tau_i \ , \qquad \tau_i = (1/d_{oi})^p,$$

$$d_{oi} = \sqrt{(x_o - x_i)^2 + (y_0 - y_i)^2} \ , \tag{10}$$

where τ_i – the weight of σ_i; d_i – the distance between the grid node o and the σ_i point; p – the weighting power; x_o, y_o; x_i, y_i are coordinates, respectively, of the o-th grid node and the i-th point. The value $p = 2$ was used to prepare the σ-grid for LAMO3 and LAMO4.

The interpolation result of (10) is rather rough and, to smooth it, the moving digital "inverse distance" low-pass filter of the size 11×11 ($5\ km \times 5\ km$ area) was used [3], [9]:

$$\sigma_{oo} = (\sum_{i,j} \sigma_{ij} \tau_{ij}) / \sum_{i,j} \tau_{ij} \ , \qquad \tau_{ij} = (1/D_{ij})^p,$$

$$D_{ij} = \sqrt{i^2 + j^2} \ , \tag{11}$$

where τ_{ij} – the weight of σ_{ij}; p – the power ($p = 0.5$ was applied); i and j are 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.

Smoothing of σ by the filter (11) is moderate. To preserve the data provided by wells, only one filtering pass 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 LAMO grid, values of transmissivity T_{ij} are computed. To obtain the permeability k-map from the T-grid, the formula (9) must be used where the m-map of thickness is the divider. Only at the aquifer $m > 0$ area, reasonable k values appear.

It has been observed in [3] that extreme k values appear within the $m = 0$ areas (there $m = 0.02$ meters for LAMO), at a vicinity of borderlines where $m \rightarrow 0$, and at locations of river valleys where the thickness takes jumpwise changes.

For LAMO3, the extreme k values at the $m = 0$ and $m \rightarrow 0$ areas were replaced by the maximal k value that was found within the $m > 0$ zone of the m-map [3]. No satisfactory method was found to eliminate the jumpwise changes of k at locations of river valleys. Partially this drawback was eased by using the filter (11) on the final k-map [3].

No nature reason exists why at the $m \rightarrow 0$ areas, high values of k should appear and no changes of k are be expected at locations of river valleys.

For LAMO4, the both above-mentioned drawbacks have been eliminated. Initial data for q have been checked.

IV. CHECKING OF WELL PUMPING DATA FOR LAMO4

Pumping data of wells were provided by LEGMC. These data were never checked before. In the case of LAMO3, only rough testing and sorting of them were done (elimination of obviously wrong data, appliance of data bounded within the $5 > q > 0.3$ interval). For the case of LAMO4, more careful checking of data was done. Its results are presented in Table II, where four stages of the initial data treatment are shown (deposited, sorted, bounded, and survived) for eight primary aquifers of LAMO. Table II gives the number of wells in each stage and the mean value q_{mean} of specific capacity of wells that are present at the stage.

The value of q_{mean} is the arithmetical mean:

$$q_{mean} = (\sum_{i=1}^{N} q_i) / N \ , \tag{12}$$

where q_i – the specific capacity of i-th well; N – the number of wells that are present at the stage.

As it follows from Table II, a rather large number of wells were not allowed to take part at the second stage "sorted". The eliminated wells were with obviously wrong data and the ones which screens were not located entirely within the aquifer under the pumping test. If a screen is located in two or more aquifers, then the well cannot be used for finding its q or its real piezometric head [10].

During the third stage "bounding", the wells are eliminated which q does not belong to the interval $4 > q > 0.2$. The value of q_{mean} increases for all aquifers, because the number of wells ($q < 0.2$) is much larger than the ones ($q > 4$).

To perform the fourth stage "survived", two sequential steps are carried out:

1st step: within a circle of the radius R_1, only the one well remains which q is the largest;

2nd step: within a circle of the radius R_2, the wells remain which hold the condition $(1 + \Delta) > q_{mean} > (1 - \Delta)$ where q_{mean} is computed for the circle and Δ is the deviation from the mean value of q_{mean}.

TABLE II
SUMMARY ON WELL DATA TREATMENT

Aquifer code	Number of wells				q_{mean}		
	deposited	selected	bounded	surviving	selected	bounded	surviving
D3ktl#	288	156	114	46	0.72	0.79	0.88
D3zg#	872	681	533	143	0.80	0.87	1.08
D3krs#	712	524	426	118	0.84	0.86	1.11
D3dg#	2284	959	819	256	1.17	1.15	1.74
D3pl	2874	1295	1073	374	1.08	1.05	1.46
D3am	778	526	420	190	0.64	0.71	0.80
D3gj2	5241	1229	1096	324	0.77	0.84	1.05
D3gj1	5346	1579	1378	425	0.82	0.88	1.18
D2brt	1867	1332	1020	367	0.71	0.80	0.99
D2ar	1740	1188	974	314	0.64	0.71	0.88

During the first step, the wells with contradictory data were eliminated, and the wells with the locally larger q were saved. The second stage is more conservative, because more than one well may be saved within the circle of the radius R_2.

For LAMO4, the following search parameters were used: $R_1 = 2000$ meters, $R_2 = 4000$ meters, $\Delta = 0.3$.

As it follows from Table II, in the stage "surviving", the number of wells is considerably reduced. The value of q_{mean} has increased, because for the both steps of the fourth stage, the wells with the locally larger q were saved.

V. OBTAINING OF PERMEABILITY MAPS FOR LAMO4

All primary aquifers of LAMO have the $m = 0$ areas. Some of them are cut by river valleys. Summary on the main geometrical features of the aquifers is presented in Table III.

TABLE III
SUMMARY ON GEOMETRICAL FEATURES OF LAMO PRIMARY AQUIFERS

Aquifer code	Area, thous. km^2	m_{mean}, meters	m_{max}, meters	m_{max}/m_{mean}	l/m_{mean}
D3ktl#	5.44	66.2	105	1.58	0.15
D3zg#	7.53	43.5	87.0	2.00	0.24
D3krs#	9.34	22.5	49.0	2.18	0.36
D3dg#	32.84	30.7	88.7	2.89	0.34
D3pl	44.10	22.7	56.0	2.47	0.55
D3am	46.52	22.1	45.3	2.05	0.53
D3gj2	51.17	26.5	58.4	2.20	0.49
D3gj1	56.66	31.8	85.8	2.70	0.51
D2brt	68.96	44.8	110.0	2.46	0.40
D2ar	68.96	30.9	98.1	3.17	0.50

It was noted above that incisions of river valleys caused jumpwise changes of k for the LAMO3 k-maps. This drawback was completely eliminated, because the m_0-maps

without incisions were used for the LAMO4 case. Such m_0-maps were applied by the LAMO1 version, and they are used even nowadays as the starting position for all necessary changes in the HM geometry (set of z-maps).

To eliminate the extreme k values, for the $m \rightarrow 0$ zone, the following correction matrix C was used:

$$1 > C = m_0 / (0.75\, m_{mean)} > 0 \qquad (13)$$

where the factor 0.75 was chosen empiricaly. The corrected q_{cor}, k_{cor} and T were obtained as follows:

$$q_{cor} = C\, q, \qquad k_{cor} = 137\, q_{cor}/m_0 , \qquad T = k_{cor}\, m, \qquad (14)$$

Table IV presents changes of q_{mean} during the interpolation and correction of q. The mean correction factor c_{cor} indirectly shows how large is the $m \rightarrow 0$ area where the correction of q took place. The larger is c_{cor} (closer to 1.0), the smaller is the area where the q-distribution is corrected by using the matrix C. In the Appendix, an example of creating the k-map for the D3pl aquifer is presented.

TABLE IV
CHANGES OF q_{mean} DURING THE INTERPOLATION AND CORRECTION STAGES

Aquifer code	After interpolation	After correction		Correction factor
	q_{mean}	q_{mean}	q_{max}	c_{cor}
D3ktl#	0.87	0.70	2.13	0.80
D3zg#	1.09	0.99	3.24	0.89
D3krs#	1.09	1.02	2.91	0.93
D3dg#	2.09	0.71	3.99	0.83
D3pl	1.48	1.37	3.61	0.91
D3am	0.749	0.71	2.38	0.95
D3gj2	1.28	1.15	3.19	0.94
D3gj1	1.21	1.14	3.28	0.94
D2brt	1.03	1.0	3.00	0.96
D2ar	0.83	0.79	3.11	0.96

VI. SUMMARY ON K-MAPS FOR THE LAMO2, LAMO3, AND LAMO4 VERSIONS

For LAMO, the k-map is presented as the following product:

$$K = K_{norm} \times k_{mean} ; \qquad k_{mean} = (\sum_{i=1}^{N} k_i)/N , \qquad (15)$$

where K_{norm} is the normalized k-map; k_{mean} and N are the mean value of k and the number of grid nodes at the $m > 0$ area, accordingly; K is the matrix that results of using the formula (14) and $K_{norm} = K / k_{mean}$ for $m > 0$ area; elements of $K_{norm} = 1$ for the $m = 0$ area.

If the k-map is applied by GV, then usually only the k_{mean} must be adjusted when HM is under calibration of the matrix A_{xy}.

In Table V, the summary on the k-maps of LAMO2, LAMO3 and LAMO4 versions is given. For each HM version,

k_{mean} and k_{max}/k_{mean} are presented. For the LAMO2 version, $k_{max}/k_{mean} = 1.0$, because constant values of k were used for all aquifers. For the LAMO3 and LAMO4 versions, the ratio k_{max}/k_{mean} is variable. For LAMO4, the ratio k_{max}/k_{mean} is larger than for the LAMO3 version, because the values $q_{min} = 0.2$ and 0.3 were used for bounding of the initial data of LAMO3 and LAMO4, correspondingly.

TABLE V

SUMMARY ON LAMO2, LAMO3 AND LAMO4 k-MAPS OF THE PRIMARY AQUIFERS

Aquifer code	LAMO2		LAMO3		LAMO4	
	k_{mean}, meter/day	k_{max}/k_{mean}	k_{mean}, meter/day	k_{max}/k_{mean}	k_{mean}, meter/day	k_{max}/k_{mean}
D3ktl#	3.0	1.0	2.12	9.0	1.77	12.10
D3zg#	3.0	1.0	3.64	5.33	3.38	15.75
D3krs#	2.0	1.0	5.95	4.35	6.33	9.89
D3dg#	10.0	1.0	5.58	14.38	9.40	16.06
D3pl	10.0	1.0	6.11	8.51	8.60	19.65
D3am	10.0	1.0	4.69	5.67	4.64	11.25
D3gj2	10.0	1.0	5.58	4.55	5.11	20.05
D3gj1	14.0	1.0	5.24	6.25	4.84	16.00
D2brt	5.0	1.0	1.91	5.83	3.19	13.75
D2ar	5.0	1.0	2.13	6.15	2.91	17.69

VII. CONCLUSION

The constant values were used for permeability maps for the HM versions LAMO1 and LAMO2. In LAMO3, the k-maps were upgraded by using the well pumping data. For current LAMO4 version, the k-maps were further improved, because the initial data of wells were checked and some other drawbacks of the former k-maps were eliminated. In future, in order to create even more realistic k-maps, the geometrical data of wells will be more accurately accounted for.

ACKNOWLEDGMENT

APPENDIX

APPLICATION OF THE WELL PUMPING DATA FOR CREATING OF K-MAP FOR THE D3PL AQUIFER OF LAMO4

In Fig. 1a, the locations of bounded wells are shown. They are not distributed evenly within the aquifer area. The number of wells $n = 1295$; $4.0 > q > 0.2$.

In Fig. 2a, the locations of survived wells are shown. The number of wells is $374 < 1295$. Data of the wells are used for creating of the grid map of q.

In Fig. 3a, the isolines for interpolated and filtered q are shown; values of q are computed in all nodes of the HM grid.

In Fig. 4a, the isolines for q after using the correction C are shown. The q distribution exists only for the $m > 0$ area of the D3pl aquifer.

In Fig. 5a, the isolines of the correction factor C are shown. The correction does not change the q distribution when $c = 1.0$; $(c_{cor})_{mean} = 0.91$.

In Fig. 6a, the isolines of the k-map are shown. There appears no trace of the valley of the Daugava river because the m_0-maps of LAMO1 were used for obtaining C and k.

In Fig. 7a, the isolines of T distribution for LAMO4 are exposed. The trace of the Daugava river valley exists there, as it should be.
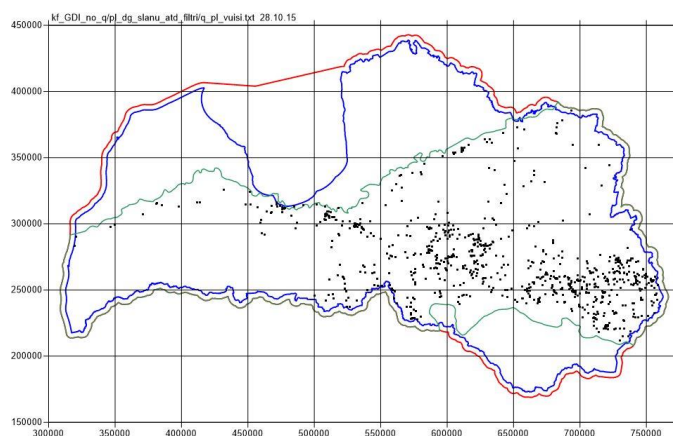

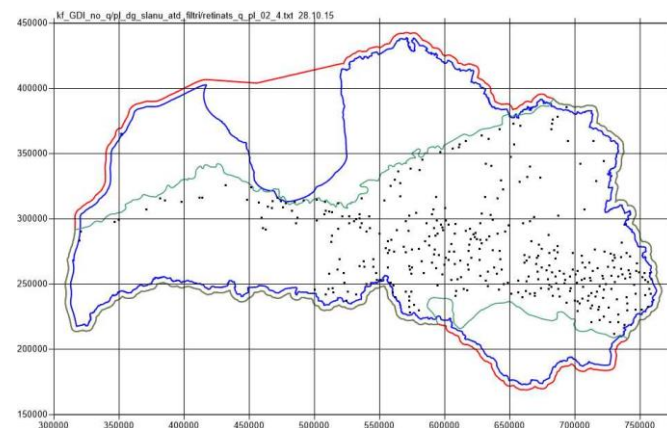Fig. 1a. Location of wells bounded for the D3pl aquifer; N=1295.

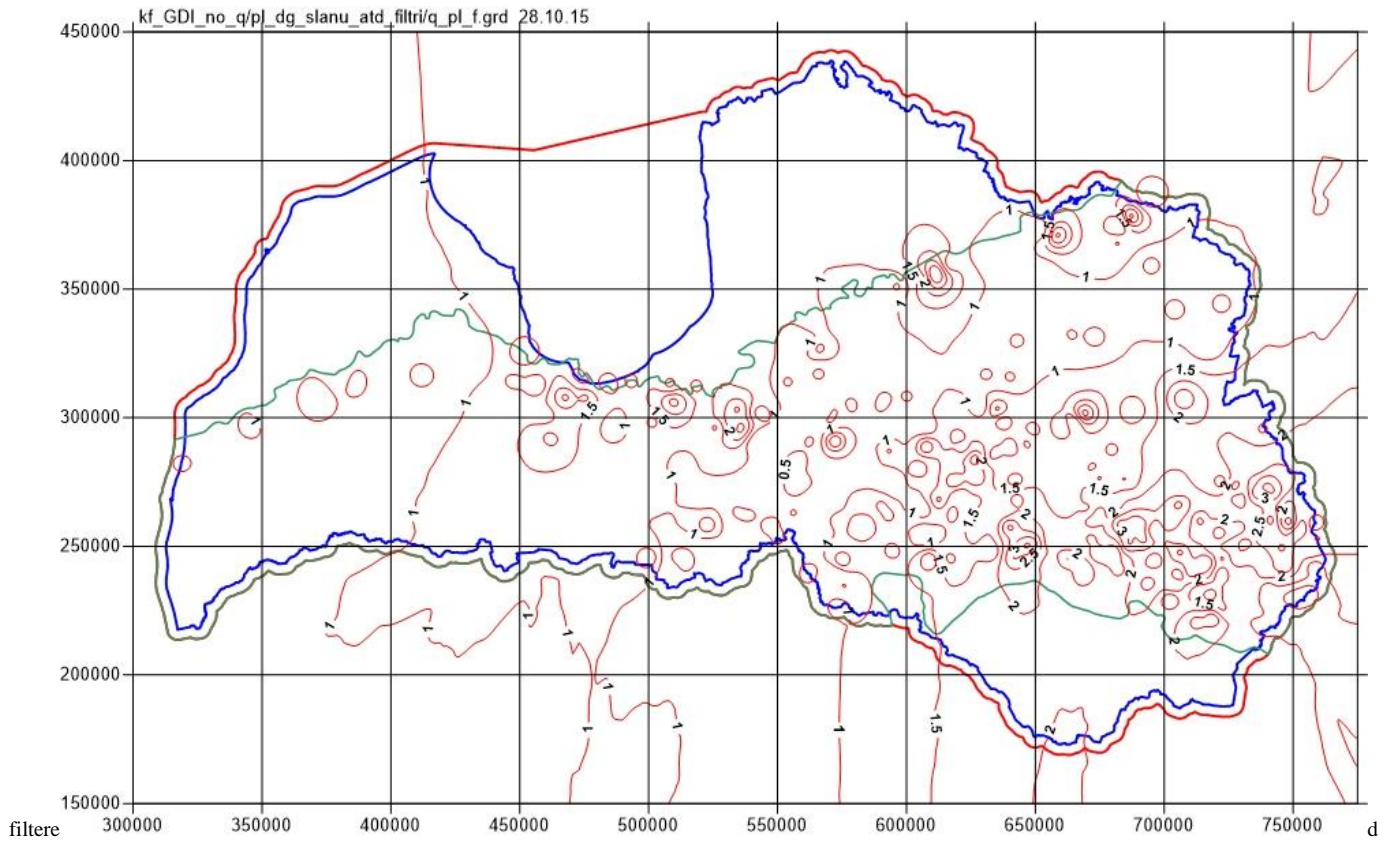Fig. 2a. Location of surviving wells for the D3pl aquifer; N=374.

kf_GDI_no_q/pl_dg_slanu_atd_filtri/q_pl_f.grd 28.10.15

filtere   d
Fig. 3a. Interpolated and filtered isolines of *q*.

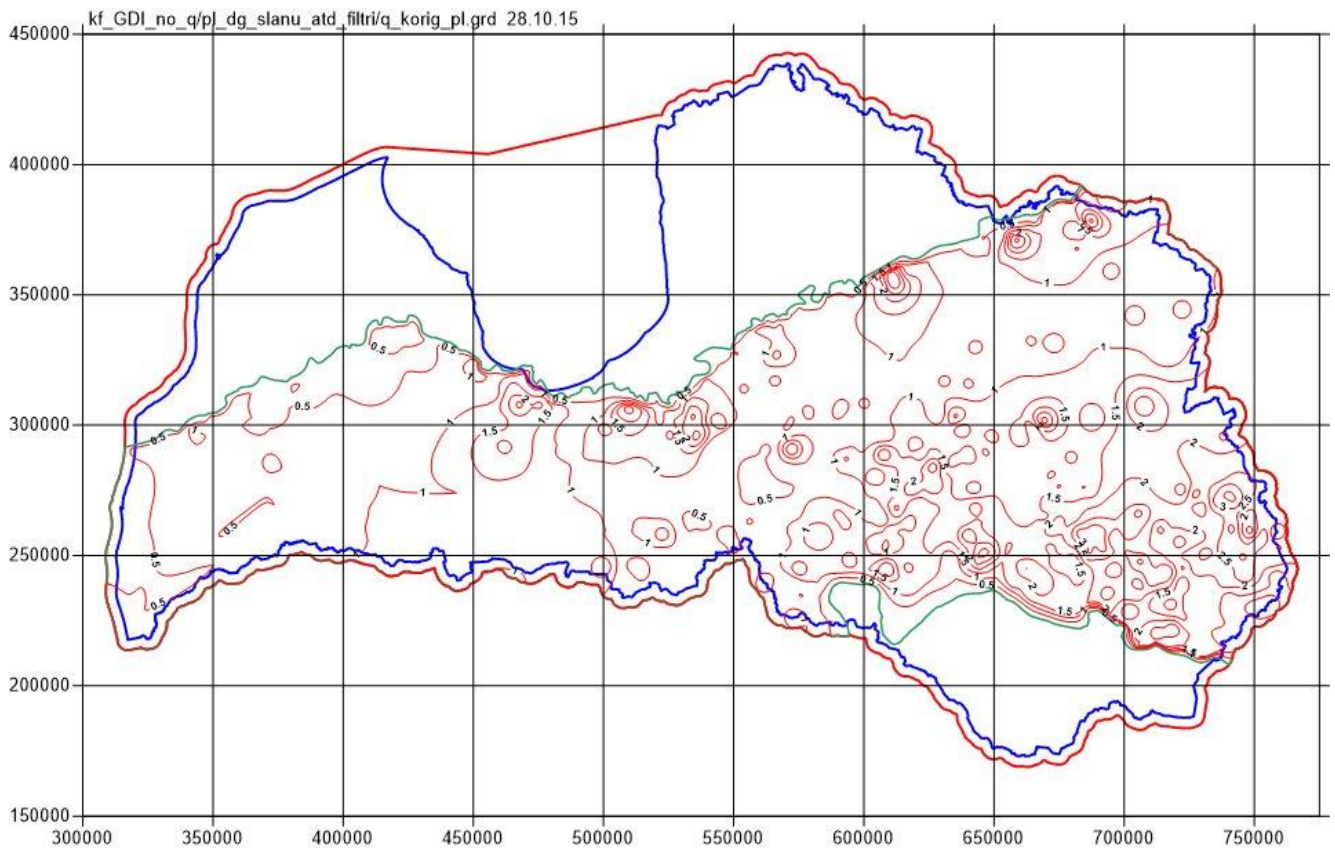kf_GDI_no_q/pl_dg_slanu_atd_filtri/q_korig_pl.grd 28.10.15
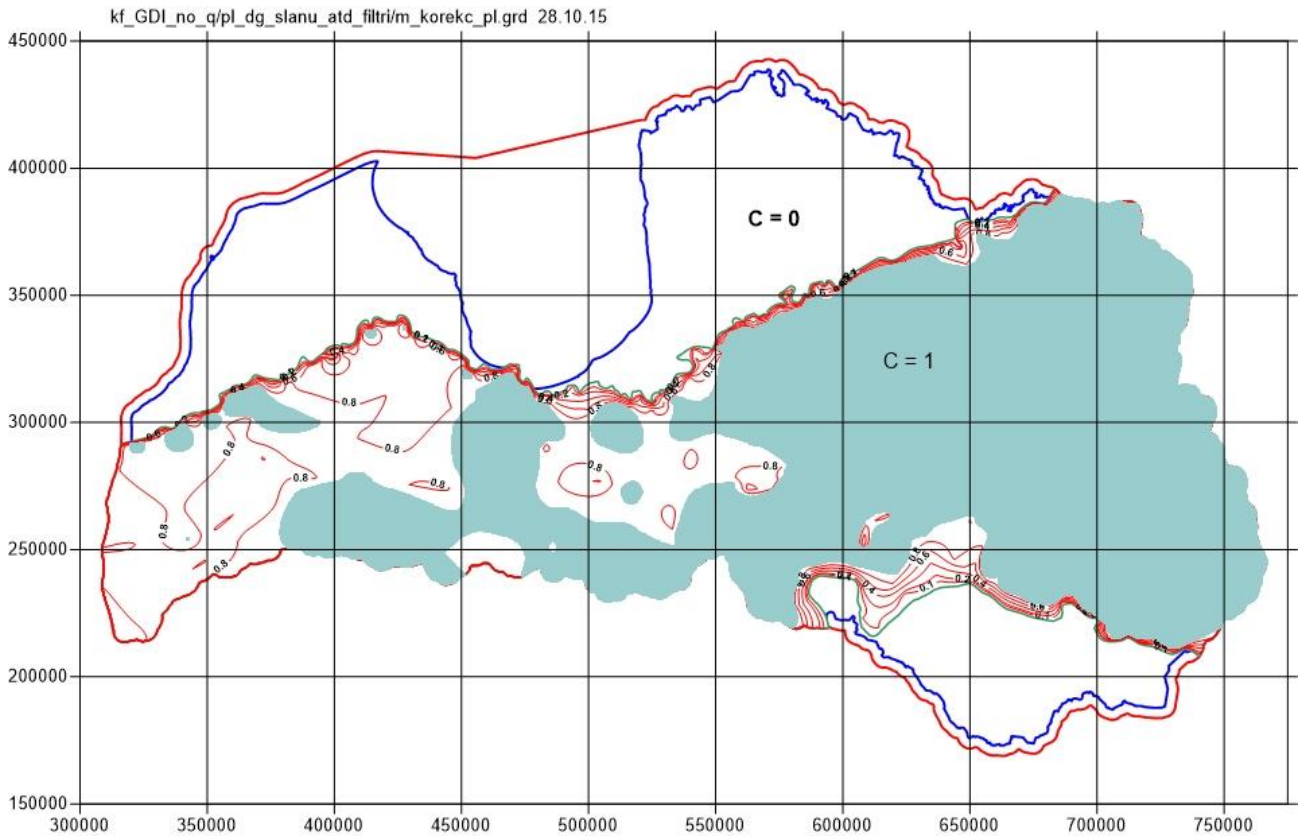
Fig. 4a. Isolines of corrected *q* (*m* >0 area).

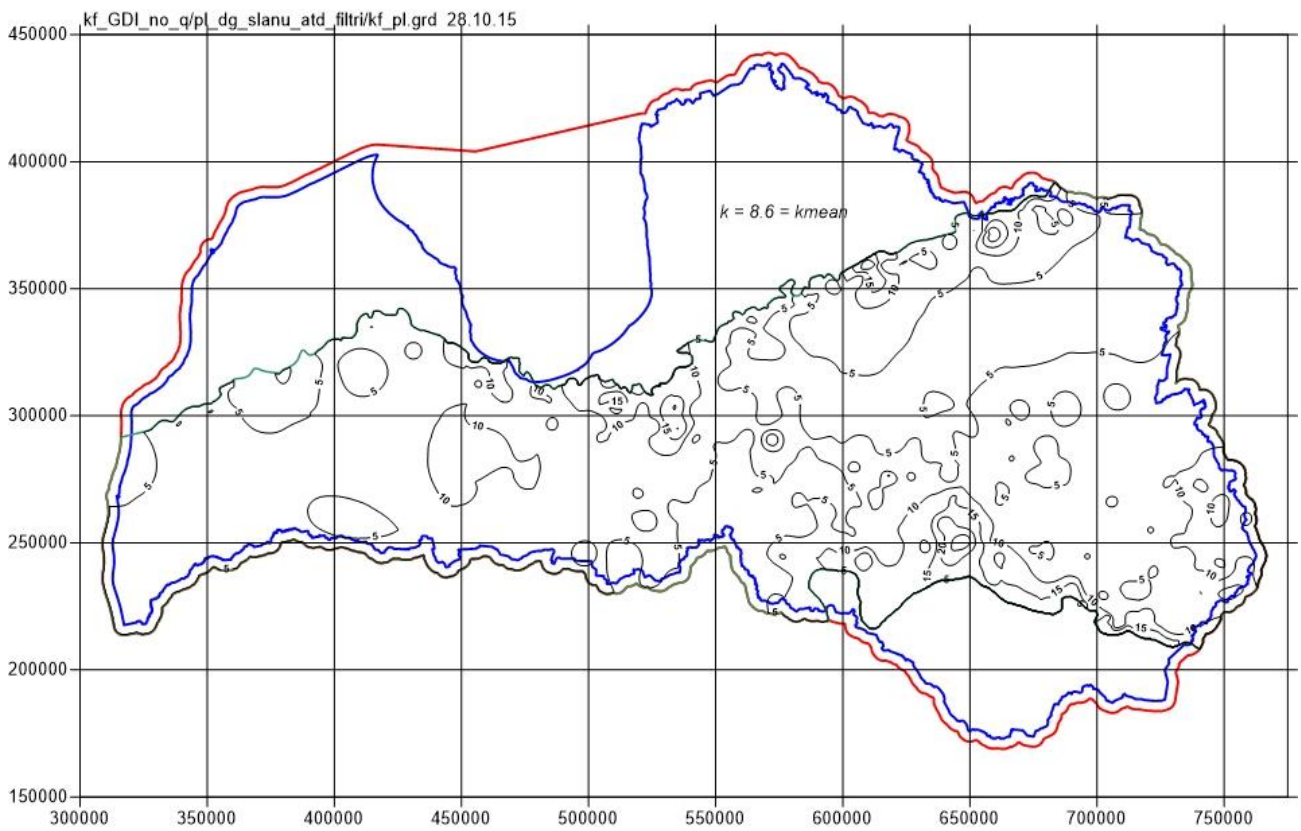Fig. 5a. Isolines of correction *C* for the D3pl aquifer (*m* >0 and *m* = 0 areas).

Fig. 6a. Isolines of the *k*-map for the D3pl aquifer.

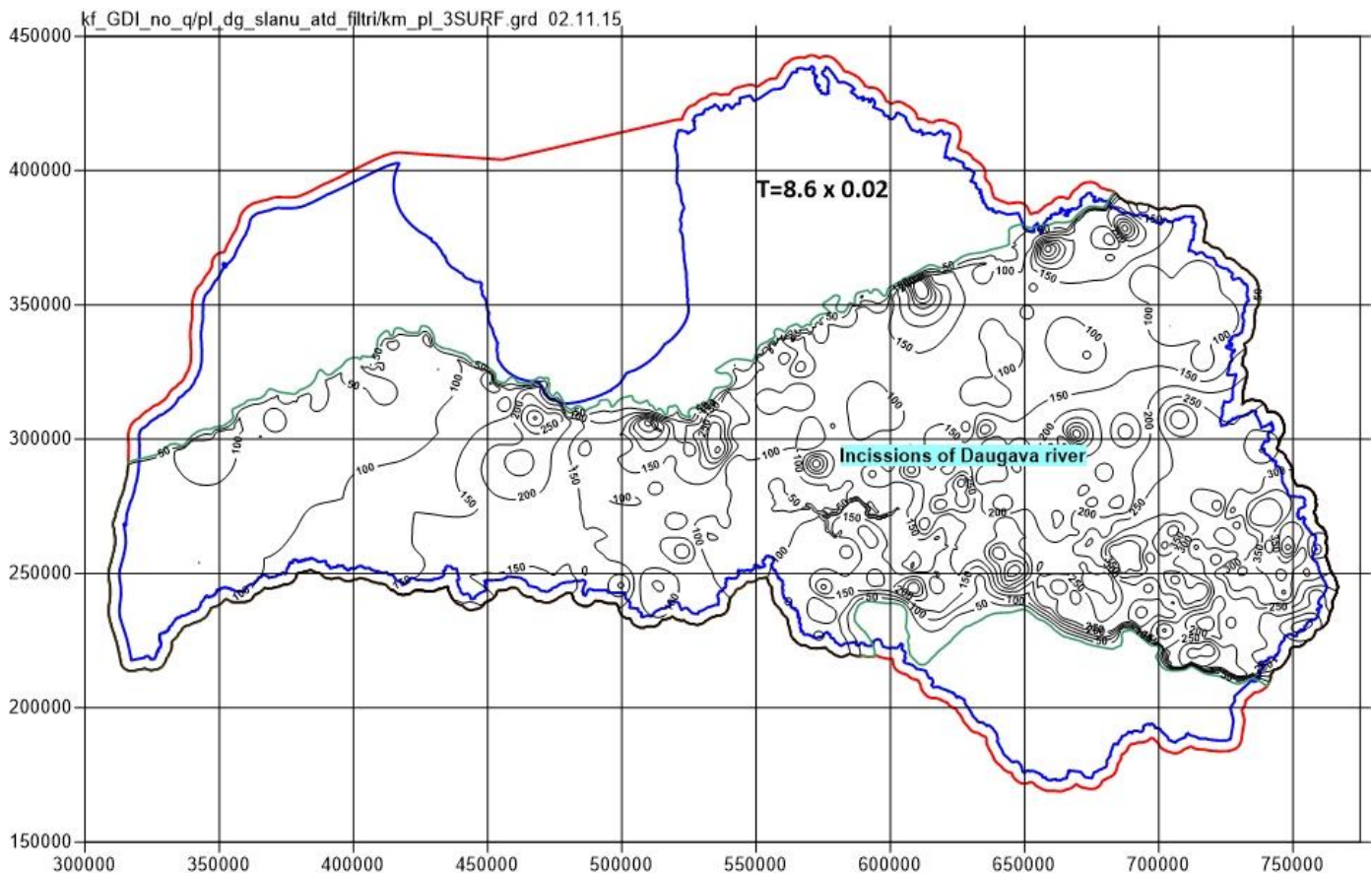kf_GDI_no_q/pl_dg_slanu_atd_filtri/km_pl_3SURF.grd 02.11.15

Fig. 7a. The final transmissivity distribution for the D3pl aquifer ($m > 0$ and $m = 0$ areas).

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