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PREFACE

"There is something irreversible about acquiring knowledge; and the simulation of the search for it differs in a most profound way from the reality."

by J. Robert Oppenheimer – American Theoretical Physicist (1904-1967)

in: "Physics in the Contemporary World" lecture at M.I.T. (25th November 1947)

For many years there is a stable growth of simulation in research with important applications. Over 30 years the European Conference on Modelling and Simulation reflects this development in many fields. Thus, this proceedings of the 30th European Conference on Modelling and Simulation (ECMS) from May 31st until June 3rd, 2016, hosted by OTH Regensburg in Germany, represents the current status.

The human capacity to abstract complex systems and phenomena into simplified models has played a critical role in the rapid evolution of our modern industrial processes and scientific research. As a science and an art, modelling and simulation have been one of the core enablers of this remarkable human trace, and have become a topic of great importance for researchers and practitioners. The increasing availability of massive computational resources and interconnectivity has helped tremendous advances in the field, collapsing previous barriers and redefining new horizons for its capabilities and applications. The scope of the accepted papers shows that this ECMS conference brings together researchers, engineers, applied mathematicians and practitioners working on these topics. In detail, these papers include methodologies, technologies, applications and tools for modelling and simulation. In our thinking, also caused by the review through recognized experts, the accepted papers demonstrate new and innovative solutions. They also highlight technical issues and challenges in this field.

The high quality of the ECMS 2016 program is enhanced by the two keynote lectures, delivered by distinguished speakers who are renowned experts in their fields: Professor Dr. Andrea Matta (Department of Industrial Engineering and Management at Shanghai JiaoTong University) and Dr. Thomas Hußlein (Managing Director of OptWare GmbH in Regensburg).

The timetable leaves enough room for various discussions and socializing. Especially, the comprehensive program with the conference dinner during a boat trip on the Danube serves to build and enhance social contacts amongst the participants.

Building an interesting and successful programme for the conference required the dedicated effort of many people; we thank them all. Especially, the authors, whose research and development efforts are recorded here, deserve our thanks. We thank the members of the Programme Committee, the Local Organization Committee and additional reviewers for their diligence and expert reviewing. Last but not least, we thank the invited distinguished keynote speakers for their invaluable contribution and for taking the time to synthesize and deliver their talks. The generosity of all sponsors allows some highlights in the social program.

All the contributions in this conference may stimulate further research. In addition, we hope that you will get valuable insights in your research area, and you will have inspiring discussions. Please enjoy the ECMS 2016 programme and your stay in Regensburg, Germany.

Thorsten Claus, Frank Herrmann, Michael Manitz and Oliver Rose
May 2016

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MAKING OF CREDIBLE PERMEABILITY MAPS FOR LAYERS OF HYDROGEOLOGICAL MODEL OF LATVIA

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KEYWORDS
Hydrogeological model, numerical interpolation, permeability of geological layers, pumping tests for wells, transmissivity of aquifers.

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 density of hydrographical network (rivers, lakes) was increased, cuttings of river valleys into primary geological layers were done, plane approximation step was decreased, hydraulic conductivity distributions of layers were refined by creating more reliable permeability maps. In the paper, methods of obtaining these maps are described.

INTRODUCTION

The countries of the European Union (EU) are developing the HM from which information is applied for the water resources management that must implement the EU aims defined in the Water Framework Directive (Water Framework Directive 2000). In Latvia, the LEGMC specialists are preparing and updating the water resources management plans for the country.

In 2010–2012, the HM LAMO was established by the scientists of RTU. LAMO simulates the steady state average hydrogeological simulation of Latvia. The licensed program Groundwater Vistas (GV) is used for running LAMO (Environmental Simulations, Inc. 2011).

Table 1: Versions of LAMO

Name of version	Year of dispo-sal	Approximation grid			Rivers in model			Lakes
		Plane step [metre]	Number of grid planes	Number of cells [$\times10^6$]	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 2013–2015, LAMO was upgraded (Spalvins et al. 2015a). Due to these upgrades, four successive versions of LAMO can be marked (see Table 1).

LAMO comprises the active groundwater zone of Latvia that provides drinking water. In Figure 1, the location of LAMO is shown.

Figure 1: Location of LAMO.

The land territory of Latvia and the area of the Gulf of Riga constitute the HM active area (Figure 2). The passive area represents border territories of the neighbouring countries. The active and passive areas are separated by the 4km wide border zone where boundary conditions for the active area are fixed.

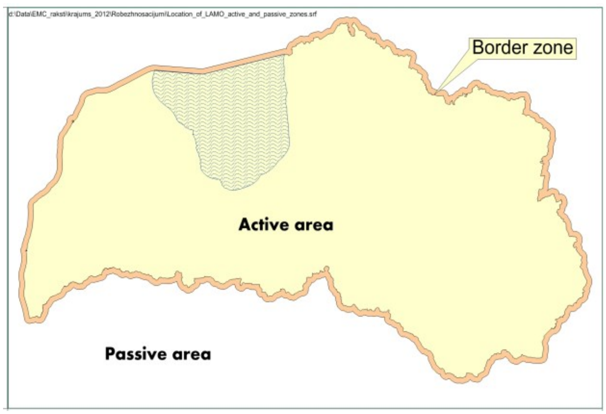

Figure 2: Locations of LAMO active and passive areas

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The LAMO4 version simulates 27 geological layers (see Table 2). It is shown in Figures 3 and 4 that most of primary layers are outcropping. After emerging at the sub quaternary surface, such layers have zero thickness ($m = 0$).

Table 2. Vertical schematization and parameters of layers for calibrated LAMO4

No of HM layer	*	Name of layer	HM layer code	Area, [thous. km^2]	m_{mean}, [meter]	k_{mean} [meter /day]
1		Relief	relh	71.29	0.02	10.0
2		Aeration zone	aer	71.29	0.02	3.1×10^{-6}
3		Unconfined Quaternary	Q2	71.29	5.77	11.2
4		Upper moraine	gQ2z	71.29	22.20	1.4×10^{-3}
5		Confined Quaternary	Q1#	7.4	6.13	7.0
6		Lower moraine	gQ1#z	9.7	9.3	2.8×10^{-4}
7		Ketleru	D3ktl#	5.32	61.46	4.2
8		Ketleru	D3ktlz	5.79	10.52	2.8×10^{-4}
9		Zagares	D3zg#	7.43	42.65	7.0
10		Akmenes	D3akz	7.95	11.05	2.8×10^{-5}
11		Kursas	D3krs#	9.34	22.34	6.3
12		Elejas	D3el#z	9.24	27.58	2.8×10^{-5}
13		Daugavas	D3dg#	32.14	30.37	9.4
14		Salaspils	D3slp#z	35.78	12.67	8.4×10^{-4}
15		Plavinu	D3pl	43.80	22.76	8.6
16		Amatas	D3am#z	45.14	8.97	1.4×10^{-4}
17		Amatas	D3am	46.21	21.91	6.4
18		Upper Gauja	D3gj2z	48.80	11.62	2.8×10^{-4}
19		Upper Gauja	D3gj2	50.92	26.34	6.2
20		Lower Gauja	D3gj1z	53.11	13.17	2.8×10^{-4}
21		Lower Gauja	D3gj1	56.13	31.55	5.4
22		Burtnieku	D2brtz	58.09	15.41	5.6×10^{-4}
23		Burtnieku	D2brt	68.74	45.02	4.2
24		Arikula	D2arz	68.74	15.02	4.2×10^{-4}
25		Arikula	D2ar	68.74	40.03	3.2
26		Narva	D2nr#z	71.29	116.67	2.8×10^{-5}
27		Pernava	D2pr	71.29	25.00	10.0

* - aquitard

m_{mean} and k_{mean} – the mean thickness and permeability

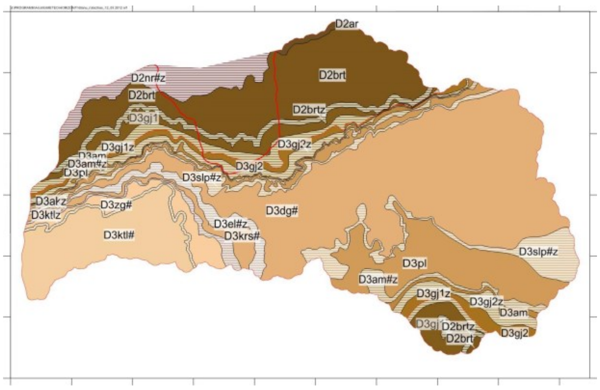

Figure 3: Boundaries of primary geological strata

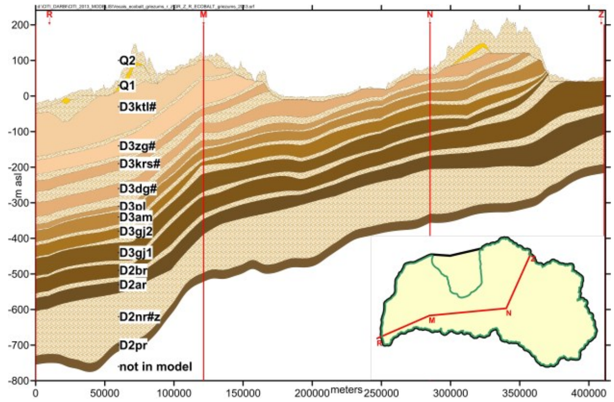

Figure 4: Geological cross section

The layers Nos 1, 2, 3, 4, 26, 27 do not have the $m = 0$ areas, because they exist everywhere in the HM area of the active part. The size of the $m = 0$ areas of the LAMO layers can be computed by using the data of Table 2. as the difference between the area of the HM active part (71.29 thous.km^2) and the $m > 0$ area of the layer.

The $m = 0$ areas caused problems when the permeability maps (k-maps) for layers of LAMO were obtained (Spalvins et al. 2015b).

In the present paper, methods are described that were used for making more realistic k–maps of LAMO4.

MATHEMATICAL FORMULATIONS

To understand the problems of creating the k-maps for the m>0 and m=0 areas of HM layers, the basic mathematics of HM must be considered

By using the 3D - finite difference approximation, the *xyz*–grid of HM is built. It 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 LAMO4, h = 250 meters.

LAMO provides the 3D-distribution of piezometric head vector φ as the numerical solution of the boundary field problem which is approximated in the nodes of the HM *xyz*-grid by the following algebraic expression (Spalvins et al. 2015a):

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

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 ψ–conditions for LAMO are fixed on all outer boundary surfaces of the HM active volume (top, bottom and the vertical surface of the shell in the

boundary zone). The ψ–conditions also include conditions for rivers and lakes. In LAMO, the β - conditions are used only for exploitation wells.
The elements a_{xy}, a_z of A_{xy}, A_z (or g_{xy}, g_z of G) for the block ($h\times h\times m_i$) are computed as follows:

$$a_{xyi} = k_i\, m_i = T_i, \qquad a_{zi} = h^2\, k_i / m_i,$$

$$m_i = z_{i-1} - z_i \geq 0, \qquad i=1, 2, \ldots, u\,, \tag{2}$$

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; for LAMO4, u=28. The set of z-maps describes the full geometry (stratification) of LAMO.
For the block (cell) of the xyz-grid, the surfaces z_{i-1} and z_i represent its top and bottom, correspondingly. The centres of the cells are located on the surface $z_{i-0.5}$:

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

The vertical link $a_{zi,i+1}$ that joins the centers of the i-th and the underlying ($i+1$)-th cell is computed, as the harmonic mean of the conductances a_{zi} and a_{zi+1} :

$$a_{zi,i+1} = 2\, a_{zi}\, a_{zi+1} / (\, a_{zi} + a_{zi+1}\,), \tag{4}$$

where a_{zi+1} is the vertical hydraulic conductivity of the (i+1)-th cell. It follows from (2) that for the m=0 areas of layers: a_{xy} = k × 0 = 0 and a_z =k/0 = ∞.
In the GV system, LAMO is supported by the MODFLOW program (Harbaugh 2005), where the matrix A must be simulated accurately also for the m = 0 areas. In order to match this rule and to avoid the "division by zero" in the a_z calculation, m = 0 must be replaced by a small $\varepsilon > 0$. For LAMO, ε = 0.02 meter.
It follows from (2), the a_{xy} and a_z–maps are computed by the GV system where the k and z–maps serve as the initial data. The z–maps simulate the geological stratigraphy that cannot be changed easily. In fact, the a_{xy} and a_z–maps can be controlled only by altering the k–maps.
For the m = 0 areas, problems arise if the k–maps for aquifers are obtained by using the formula:

$$k = T / m\,, \tag{5}$$

where the m-map is the divider. For the m = 0 areas of aquitards, obstacles of obtaining their k-maps also must be removed.

PERMEABILITY MAPS FOR AQUITARDS

The basic indication of an aquitard which impedes flow of groundwater is its small value of k (see Table 2). Due to this fact, the transmissivity $a_{xy} = T$ of aquitards has no real influence on the solution φ of (1). Due to smallness of a_{xy}, no boundary conditions are used for aquitards. As it follows from (4), the vertical link a_{zi} of an aquitard takes over the link a_{zi+1} of an aquifer, because $a_{zi+1} >> a_{zi}$ and $a_{zi,i+1} \sim a_{zi}$. For this reason, the aquitards control vertical groundwater flows between the aquifers.
The k–maps of the aquitards of LAMO were obtained by using general knowledge about aquitards of Latvia and by adjusting the maps in the course of calibration.
Special correction of the k–maps was done for the m = 0 areas of the ten aquitards Nos 6, 8, 10, 12, 14, 16, 18, 20, 22, 24. At the northern part of Latvia, their m = 0 areas are overlapping with those of the eleven aquifers Nos 5, 7, … ,25. (see Table 2, Figures 3 and 4). For the 21 cells of the size $(h\times h\times\varepsilon)$, the series conductance a_{zn} of the volume $(h\times h\times 21\varepsilon)$ can be computed by using the expression for the series connection of a_{zi} :

$$a_{\mathrm{zn}} = 1 / \sum_{i=1}^{n} (1 / a_{zi}) = (h^2 / \varepsilon) / \sum_{i=1}^{n} (1 / k_i)_{mean} = 32\,, \tag{6}$$

where $k_i = k_{mean}$ are the data in Table 2; h = 250; n = 21. It is obvious that the value a_{zn} = 32 cannot be accepted, because it is very far from $a_z = \infty$. To mend a_{zn} at the m = 0 areas, the k_{mean} was increased 100 and 10 times, for the aquitards Nos 8, 10 and Nos 12-24, accordingly. After the correction, the value of k_{zn} increased from the unacceptable 32 to 934.
Within the m > 0 area of an aquitard, the m = 0 track can appear if the aquitard is cut through by a river valley. These tracks are treated as the ordinary m = 0 areas.
The choice of ε = 0.02 meter was determined also by the tolerable error of stratification in the m = 0 areas for the northern part of Latvia. There the total thickness of the m = 0 volume is 21ε. If ε = 0.02 then there the HM geometry distortion 1.02 meter is acceptable.

PERMEABILITY MAPS FOR AQUIFERS

The transmissivity a_{xy} for aquifers is very important, because it controls the lateral groundwater motion there. Because a_z of aquifers have large values, they have small influence on vertical links of (4), hence in LAMO they join aquifers with aquitards.
The permeability of aquifers can be found in a variety of ways: field tests, laboratory tests, methods based on grain size distributions (Domenico and Schwartz 1998). Inverse problem solving methods can also be used (Chin 2014). However, the field tests where one well is pumped are commonly applied. They permit the testing of large volumes of rock. They have provided rather reliable data for finding permeability of aquifers for the LAMO3 and LAMO4 versions
It was shown in (Spalvins et al. 2015b), how the variable k-maps were obtained for the LAMO3 version by using the pumping data of wells. New methods that have been used for creating more reliable k-maps for the LAMO4 version are described in this section.

Appliance of pumping data of wells

The 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 (Bindeman and Jazvin 1982):

$$S = \frac{Q}{2\pi T}(\ln(R/r) + \xi + \gamma)\,, \quad T = km, \qquad (7)$$

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 (7).

From (7), the following expression can be obtained:

$$T = \frac{q}{2\pi}(\ln(R/r) + \xi)\,, \qquad q = Q/S\,, \qquad (8)$$

where q is the specific capacity of a well.

If q and T have the dimensions, liter/(sec.meter), and $(\text{meter})^2$/day, respectively, then

$$T = 13.75q(\ln(R/r) + \xi)\,. \qquad (9)$$

It was shown in (Spalvins et al. 2015b) that for the leaky confined primary aquifers of LAMO, $ln(R/r)$ ~10.0. If ξ=0 then (9) is roughly approximated by the expression:

$$T_{\min} = 137q. \qquad (10)$$

In (Verigin 1962), the empirical formula is given for obtaining ξ:

$$\xi = (1/a - 1)(\ln 1.47ab - 2.65a)\,,\ a = l/m,\ \ b = m/r, \quad (11)$$

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:

$$T = v\,T_{min}\,, \quad v = 1 + \xi / 10.0\,, \quad k_{cor} = v\,k\,, \qquad (12)$$

where k_{cor} – the corrected value of k.

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 follows from (Spalvins et al. 2015b), the correction factor v may be within the limits: $2.8 > v > 1.3$.

Presently, ξ is not accounted for. However, (12) shows that a modeler can use $T > T_{\min}$, if necessary. It was done for the LAMO4 version (Spalvins et al. 2015a). In Table 2, k_{mean} have larger values than the ones in Table 4 where $v = 1.0$.

Obtaining of permeability maps

The k-maps for aquifers can be obtained by using the formula (5) 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 (Walkenback 2007), the set of the specific capacity q, 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 (Golden software, Inc 2012) This method computes the interpolated value σ_o at the grid nodes by using the available pointwise data $\sigma_i = q_i$, $i = 1,\dots,n$, as follows (Franke 1982):

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

$$d_{oi} = \sqrt{(x_o - x_i)^2 + (y_0 - y_i)^2}\,, \qquad (13)$$

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 (13) is rather rough and, to smooth it, the moving digital “inverse distance” low-pass filter of the size 11×11 was used (Spalvins et al. 2015b), (Ditas 2000):

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

$$D_{ij} = \sqrt{i^2 + j^2}\,, \qquad (14)$$

where τ_{ij} – the weight of σ_{ij} ; p – the power ($p = 0.5$ was applied); i and j were 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 $\sigma = q_{ij}$ by the filter (14) 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 q_{ij} are computed. Because the formula (5) are used, only at the $m > 0$ area, reasonable k values may appear.

Very large k values appear within the $m = 0$ areas (there $m = 0.02$ meter for LAMO), at a vicinity of borderlines within the $m > 0$ areas where $m \to 0$. At locations of river valleys, the values of k jumpwise enlarge, due to the decrease of m at the valley places.

For LAMO3, the extreme k values at the $m = 0$ and $m \to 0$ areas were replaced by the maximal k value that was found within the $m > 0$ zone of the k-map (Spalvins et al. 2015b). No satisfactory method was found to eliminate the jumpwise changes of k at the locations of river valleys.
For LAMO4, the both above-mentioned drawbacks were eliminated. Initial data for q were checked by the computer based tools.

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 3, where four stages of the initial data treatment are shown (deposited, sorted, bounded, and surviving) for the ten primary aquifers of LAMO. Table 3 gives the number of wells in each stage and the mean value q_{mean} of the specific capacity of wells that are present at the stage.
The value of q_{mean} is the arithmetic mean:

$$q_{\text{mean}} = (\sum_{i=1}^{N} q_i)/N \, , \tag{15}$$

where q_i – the specific capacity of i-th well; N – the number of wells.
As it follows from Table 3, a rather large number of wells were not allowed to take part at the second stage “selected”. 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 the real piezometric head of the aquifer (Tremblay et al. 2015).
For the aquifers D3gj1 and D3gj2, due to this feature, a considerable part of their wells were not accepted for the second stage (see Table 3).
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 “surviving”, two sequential steps are carried out:
1-st step: within a circle of the radius R_1, only the one well remains which q is the largest;
2-nd 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 within the circle and Δ is the deviation from the value of q_{mean}.
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.

Table 3: Summary of 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

For LAMO4, the following search parameters were used: $R_1 = 2000$ meters, $R_2 = 4000$ meters, $\Delta = 0.3$.
As it follows from Table 3, in the stage “surviving”, the number of wells is considerably reduced. The value of q_{mean} increased, because for the both steps of the fourth stage, the wells with the locally larger q were saved.

Correction of permeability maps for aquifers

The primary aquifers of LAMO have the $m = 0$ areas. Some of them are cut by river valleys
It was noted above that incisions of river valleys into primary layers caused jumpwise increases of k for the LAMO3 k-maps. This drawback was completely eliminated, because the m_0-maps without the incisions were used for the LAMO4 case. Such m_0-maps have been 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).
Appliance of the m_0-maps is founded on the assumption, that a river valley does not change k.
To suppress the extreme k values, for the $m \to 0$ zone, the following correction matrix C was used:

$$1 > C = m_0 \,/\, (0.75 \, m_{\text{mean}}) \geq 0 \, , \tag{16}$$

where the factor 0.75 was chosen empirically; within the $m = 0$ and $m > 0$ areas, C=0 and 1, respectively. The corrected q_{cor}, k_{cor} and T are obtained, as follows:

$$q_{\text{cor}} = C\, q, \qquad k_{\text{cor}} = 137\, q_{\text{cor}}/m_0 \, , \qquad T = k_{\text{cor}}\, m. \tag{17}$$

In (17), the real m-map is used for obtaining of T and, at locations of river valleys, the values of T take jumpwise decreases, as it must be.
For the $m > 0$ area of an aquifer, the mean arithmetical value k_{mean} of k_{cor} must be found. Within the $m = 0$ area, $k_{\text{cor}} = 0$ must be replaced with k_{mean}. The replacement secures the space continuity of HM in the z–direction. In

nature, the continuality of the geological environment is secured by its zero thickness $m = 0$.

In LAMO, the matrix K_{norm} that results from (17), is used as the product:

$$K_{cor} = K_{norm} / k_{mean} , \qquad (18)$$

where $k_i = 1.0$, in the $m = 0$ areas of K_{norm}.

In order to decrease a_{xy} in the $m = 0$ areas, (ideally. there $a_{xy} = 0$), K_{cor} elements there are multiplied by 0.1.

Summary on the k-maps

In Table 4, the summary on the k-maps for primary aquifers of the 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 4: 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

For the LAMO3 and LAMO4 versions, the use of more realistic k-maps for primary aquifers caused changes of their groundwater flow balances (Spalvins et al. 2015a).

CONTROL OF PERMEABILITY MAPS

In MODFLOW and LAMO, the k and m-maps, from the viewpoint of mathematics, are diagonal matrices which elements exist only in nodes of the xyz – grid of HM. For the matrix A of (1), the elements a_{ij} that join the neighbouring nodes with the indices i and j, are computed by MODFLOW as the harmonic mean of a_{xy}, a_z of (2), accordingly, for the lateral and vertical links. No connections exist between the grid nodes that are not neighbours and these links have the zero value. Due to this short-range feature of the geological environment, the matrix A is sparse, because it contains only $7N \ll N^2$ nonzero elements (N is the number of nodes; N^2 is the number of elements of A). The matrix A is symmetric, because its elements $a_{ij} = a_{ji}$ (Strang 1976).

In LAMO, the final k-map is represented by the diagonal matrix K that is the product of the six factors:

$$K = K_1 \times K_2 \times \ldots \times K_6, . \qquad (19)$$

Table 5 provides the summary on appliance of these six factors K_i for aquitards and aquifers. The factor k_{mean} and the identity matrix I are scalars. The matrix I acts like multiplication by 1; the symbol "+" indicates appliance of the corresponding factor.

Table 5: Factors for controlling the k-maps of LAMO

Factor		Aquitards		Aquifers	
code	action	others	aer	others	Q2
K_1	core matrix	I	1and 0.05	K_{norm}	K_{norm}
K_2	k_{mean}	+	+	+	+
K_3	change of k	+	+	+	+
K_4	alter k for $m = 0$	1 and 10 1 and 10^2	I	1 and 0.1	I
K_5	alter k for shell	1 and 10^3	1 and 10^3	I	I
K_6	change of m	I	+	I	+

The role of the four factors $K_1 – K_4$ is similar for the all HM layers:

- K_1 is the core matrix; for aquitards and aquifers, accordingly, $K_1 = I$ and K_{norm} ; for the aer zone, the values 0.05 are applied for areas of swamps and locations of lakes and rivers;
- $K_2 = k_{mean}$ for all layers;
- K_3 is the matrix that is variable during the HM calibration; K_3 is created by using the original GDI (Geological Data Interpolation) program that applies lines as data carriers (Spalvins et al. 2013);
- K_4 accounts for the necessary changes of k for the $m = 0$ areas of layers;
- K_5 is used only for the $m > 0$ areas of the border zone of aquitards where the factor 1000 turns the HM shell into the interpolation tool of the ψ-conditions (Spalvins et al. 2013);

The treatment of the layers Nos 2 and 3 (aer and Q2) after the HM calibration is special, because their thicknesses may be changed, if necessary. During the calibration, $m_{aer} = 0.02$ meter (see Table 2). The layer aer is the formal aquitard that controls the infiltration flow on the HM top. It is shown in (Spalvins et. al. 2013) how the thicknesses m_{aer} and m_{Q2} can be changed, if the appliance of the real m_{aer} is needed. Then the factor K_6 is used.

The aquifers Nos 1 and 27 carry the ψ–conditions and no special data are needed to control them. For this reason, all their six factors K_i are I.
During the HM calibration, the factors K_2 and K_3 must be adjusted..

CONCLUSION

For the present LAMO4 version, the permeability maps were considerably upgraded both for aquifers and aquitards. The more realistic maps of aquifers were created by accounting for pumping data of exploitation wells. The data were checked by computer – based inventory tools. Some drawbacks of the maps that were used in the previous LAMO versions were eliminated. The methods that were used for creating of the LAMO4 permeability maps would be applied by modelers dealing with large regional hydrogeological models.

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