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A HYDROGEOLOGICAL MODEL AS A TOOL FOR INVESTIGATING THE PROCESSES OF NATURE: A CASE STADY OF THE IECAVA RIVER BASEFLOW, LATVIA

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ABSTRACT

In 2010–2012, the hydrogeological model (HM) of Latvia (LAMO) was established by the scientists of Riga Technical University (RTU). In 2013–2014, LAMO was upgraded. In 2015, the recent version LAMO4 was developed. In LAMO4, the plane approximation step was decreased from 500 meters to 250 meters. The baseflows of rivers for HM were adjusted by accounting for data that were provided by the measurements of river streams. LAMO is run by the licensed program Groundwater Vistas (GV), version 6. It contains the MODFOW and MODPATH programs for supporting HM and for tracking groundwater particles, respectively. By using MODPATH, the case of the Iecava river was investigated, in order to find the sources that support groundwater inflow into the river (its baseflow). Unforeseen results were obtained. Due to the appliance of LAMO4, it was discovered that some part of the river baseflow comes from the areas that are located very far from the river drainage basin. It also was not expected that even within the basin, the particle traces were very complex. The results described in the paper serve as demonstration for the usefulness of applying a large complex HM for investigating the processes of nature.

Keywords: baseflow of river, hydrogeological model, particle tracking, Latvia.

INTRODUCTION

In 2010 – 2012, HM LAMO was developed and, in 2013 – 2015, it was upgraded by scientists of RTU [1]. Presently, four successive versions of LAMO can be marked (Table 1). LAMO comprises the active groundwater zone that provides drinking water.

LAMO is run by the licensed GV program [2]. It contains the MODFLOW [3] and MODPATH [4] programs for supporting HM and for tracking groundwater particles, accordingly.

The location of LAMO is shown in Fig. 1. Most of geological layers are outcropping and, for this reason, they are not present everywhere in the HM area (see Fig. 2). After emerging at the sub quaternary surface, such layers have the zero thickness $m = 0$. To avoid in GV calculations “the division by zero”, $m = 0$ was replaced by small $\varepsilon > 0$ (for LAMO, $\varepsilon = 0.02$ meter). It follows from the HM vertical schematization (Table 2) that the current version of LAMO4 simulates 27 geological layers.

By using LAMO4, the first attempt has been done to use this large regional HM as a tool for investigating the processes of nature by searching for sources that support the baseflow of a river. The case of the Iecava river was explored. The river is located in the flat land area of the country (Fig. 3). Its elevations are 68.5 m asl and 0.2 m asl for the source and mouth of the river, accordingly. The drainage basin area is 1174 km^2. It includes the area of the small tributaries Smakupe and Girupe.

Table 1: Versions of LAMO

Name of version	Year of disposal	Approximation grid			Rivers in model			Lakes
		Plane step [meter]	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

Fig. 1. Locations of LAMO and the Iecava river drainage basin

Table 2: Vertical schematization of LAMO4

No of HM layer	*	Name of layer	HM layer code	Area, [thous. km^2]
1		Relief	relh	71.29
2		Aeration zone	aer	71.29
3		Unconfined Quaternary	Q2	71.29
4		Upper moraine	gQ2z	71.29
5		Confined Quaternary	Q1#	7.4
6		Lower moraine	gQ1#z	9.7
7		Ketleru	D3ktl#	5.32
8		Ketleru	D3ktlz	5.79
9		Zagares	D3zg#	7.43
10		Akmenes	D3akz	7.95
11		Kursas	D3krs#	9.34
12		Elejas	D3el#z	9.24
13		Daugavas	D3dg#	32.14
14		Salaspils	D3slp#z	35.78
15		Plavinu	D3pl	43.80
16		Amatas	D3am#z	45.14
17		Amatas	D3am	46.21
18		Upper Gauja	D3gj2z	48.80
19		Upper Gauja	D3gj2	50.92
20		Lower Gauja	D3gj1z	53.11
21		Lower Gauja	D3gj1	56.13
22		Burtnieku	D2brtz	58.09
23		Burtnieku	D2brt	68.74
24		Arikula	D2arz	68.74
25		Arikula	D2ar	68.74
26		Narva	D2nr#z	71.29
27		Pernava	D2pr	71.29

* - aquitard

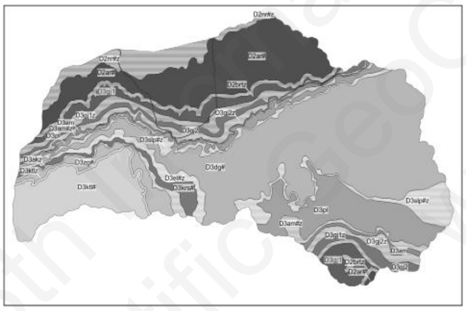

Fig. 2. Boundaries of primary geological

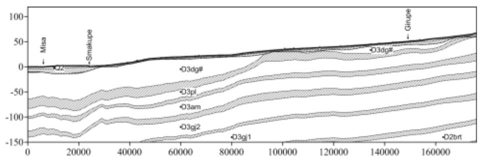

Fig. 3. Locations of the Iecava river and its drainage basin.

Fig. 4. Vertical cross-section along the Iecava river (above -150 m asl)

In Fig. 4, the vertical cross section (above -150 m asl) along the Iecava river is shown. It follows from the exposed stratigraphy that the river drainage basin does not include the layers Nos 5–12 of Table 2, because they do not exist there. The Iecava river lies into the aquifer Q2, and the primary aquifer D3dg# is located just beneath the river.

Table 3. Groundwater flow, thous. m^3/day,
balance for the drainage basin of the Iecava river

Object	q_{topin}	q_{topout}	q_{botin}	q_{botout}	q_{inflow}	q_{river}	q_{lake}	q_{border}	q_{well}
Basin	172	−31			141	−147	0	9	−3
Q2	167	−31	93	−93	136	−135	0	−1	0
Primary	5				5	−12	0	10	−3

In Table 3, the groundwater flow balance for the drainage basin of the Iecava river is presented. It was obtained by using the GV mass balance tool [2]. The following conclusions can be drawn from the data of Table 3:

- through the drainage basin border, a notable inflow q_{border} = 9 thous. m^3/day exists; it contains mainly the flow of the primary layers (10 thous. m^3/day);
- the Iecava river is connected not only with the Quaternary but also with the primary D3dg# layer (q_{river} = −147= −(135+12), respectively;
- the flows q_{botin} and q_{botout} for the Q2 aquifer are equal (± 93 thous. m^3/day).

It will be shown later that data of Table 3 partly explain the results on finding the sources that support the baseflow $q_{river} = -147$ thous. m^3/day of the Iecava river. The search was accomplished by the MODPATH program. In Fig. 1, the locations are shown of the Iecava river drainage basin and the large area outside the basin where the baseflow sources also were found. In this paper, the unforeseen results of this numerical experiment are described.

MATHEMATICAL FORMULATIONS

To explain the role of the baseflow of a river in HM, some mathematics of the steady state 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. The model constitutes a rectangular u-tiered *xy*-layer system where u is the number of geological layers. For LAMO4, u = 27 (Table 2).

LAMO provides the 3D-distribution of piezometric head vector $\varphi(x,y,z)$ 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 [1]:

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

where A is the 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.

In GV, the flow for rivers q_{rivers} (baseflow) is simulated as follows [1]:

$$q_{\text{rivers}} = G_{\text{rivers}} (\varphi - \psi_{\text{rivers}}), \tag{2}$$

where G_{rivers} is the diagonal matrix (part of G) that assemble the elements linking the boundary condition ψ_{rivers} (part of ψ) for the rivers with nodes of HM. These links control the interaction of the HM body with the rivers. In LAMO4, the elements of G_{rivers} have been adjusted by accounting for data provided by the real measurements of the river streams [1]. In (2), ψ_{rivers} and φ are vectors of the water profile of a river and the groundwater head at the HM grid node, accordingly.
The MODPATH program computes the 3D-pathlines for imaginary "particles" of water moving through the simulated groundwater system [4]. MODPATH also computes the time of travel for the particles (age of groundwater). In nature, groundwater migrates in the downgradient direction.
For a river, the starting locations of particles coincide with the cells where the river is attached to the HM body. These locations are fixed by the data carried by (2). The Iecava river is linked with HM in 1027 nodes. In 985 and 42 nodes, accordingly, links belong to Q2 and D3dg# aquifers. To find a pathline which reaches an unknown source of the river flow, the "reverse" tracking regime of MODPATH was applied when a particle moved in the upgradient direction. The particle stops and finds its source when it reaches a surface where the ψ-type boundary conditions of (1) are fixed. It mostly happens on the top surface of HM (1st layer) where the ψ_{rel} -condition is set. Then the sources are meteoric water (rain, show). Some particles move down towards the bottom surface of HM (27th layer), where the ψ_{D2pr} – condition is set. Then their sources are located beneath the thick regional aquitard D2nr#. If a river is located close to the border of HM, the sources may be located on the border side surface where the ψ–conditions also are fixed. In nature, a particle moves from the source to a river.

FINDING BASEFLOW SOURCES FOR THE IECAVA RIVER

The Iecava river is an ordinary flat-land river that has a small specific slope (see Fig. 3. and Fig. 4.). The 1027 cells joined with the Iecava river were used as the particle starting locations. None of the two small tributaries (Smakupe and Gerupe) were involved, in order to make the numerical experiment simpler. The porosity value 0.1 was used for all layers of HM. The travel time of particles was not limited.
It was expected that the baseflow should be originated by meteoric water of the river drainage basin. However, the result (Fig. 5) was a surprise, because many baseflow sources were located far from the river drainage basin. Their pathlines sank down, moved sidewise and climbed up to the river. In Fig. 5, to show the results explicitly, only the each tenth pathline in turn is exposed.
In Fig. 6, the relationship between the number of particles and the length of their pathlines is shown. It can be deduced from the data of Fig. 6 that for 830 particles, the length of their pathlines does not exceed 20 kilometers; therefore,~80 % of the particles have rather short pathlines.

In Fig. 7, the maximal travel time spent by the particles in the layers of HM is shown. Probably, the travel times that exceed 4000 years are spent by the particles with long pathlines. The time 30 thousand years is spent by the particles in the thick D2nr# aquitard (layer No. 26).

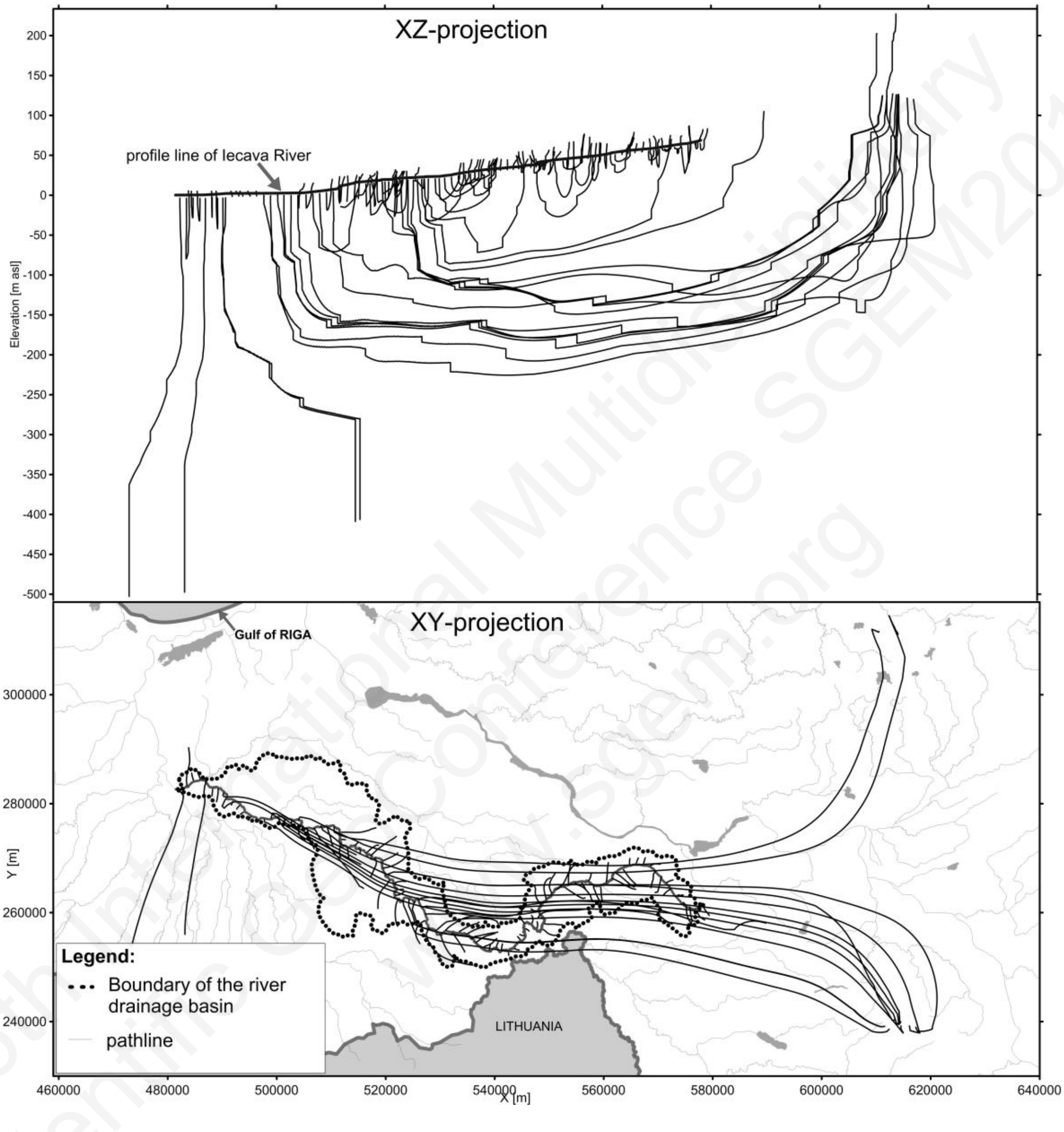

Fig. 5. Display of *xy* and *xz*-projections for pathlines.
Only the each tenth pathline in turn is exposed (~100 pathlines from 1027).

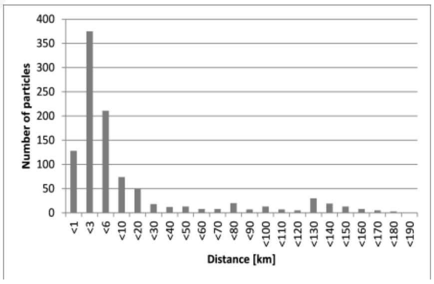

Fig. 6. The length of pathlines versus their number

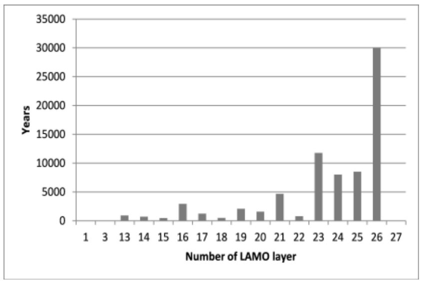

Fig. 7. Maximal travel time within

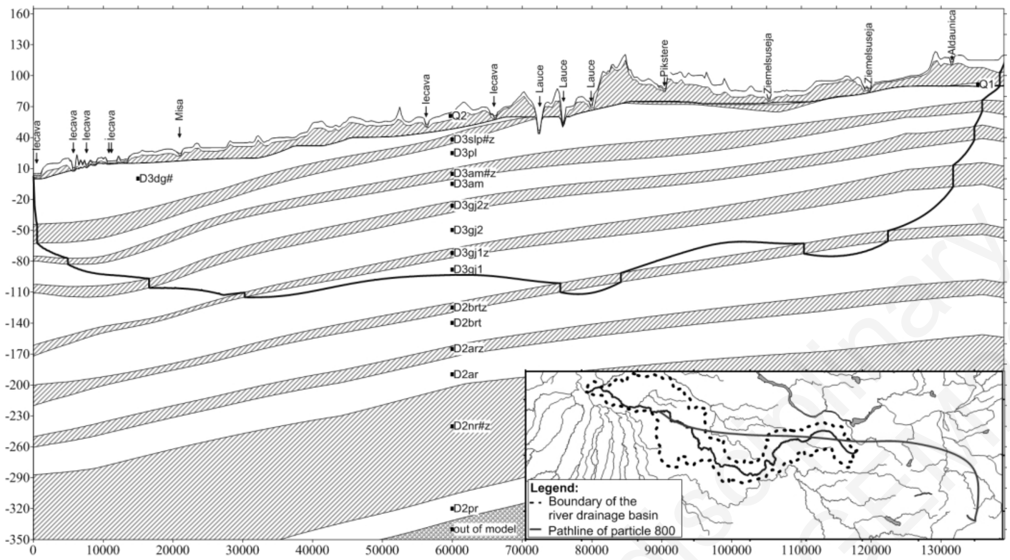

Fig. 8. Vertical cross section along the pathline No. 800.

In Fig. 8, the *ly*-projection for the particle No. 800 along its pathline is shown. Its travel time (age) is 8015 years. The cross section was created by using SURFER [5] and the special software tools developed by the RTU specialists.

It can be concluded from Fig. 8 that the appearance of the long pathlines which sources are located far from the drainage basin is caused by the infiltration at the hilly areas of the country. There, a particle can reach a deeply located aquifer and then migrate a long distance, until the Iecava river is reached. In Fig. 8, the particle passes through the D2brtz aquitard four times. This fact is caused by the vertical groundwater flows at the places where the particle enters the D2brt aquifer and then returns in the D3gj1 aquifer.

SORTING OF PATHLINES

The above analysis of the simulation results for the Iecava river was done without sorting of pathlines obtained by the MODPATH program. The pathlines were sorted in seven groups by the EXCEL program [6] (Table 4) by taking into account their tracking time (age of groundwater)

Table 4. Groups of sorted pathlines

No. of group	Time, years	Number of pathlines
1	0>25	259
2	0>25–100	295
3	0>100–400	198
4	0>400–1600	68
5	0>1600–6400	84
6	0>6400–128000	86
7	0>128000–35530	37
		In total, 1027

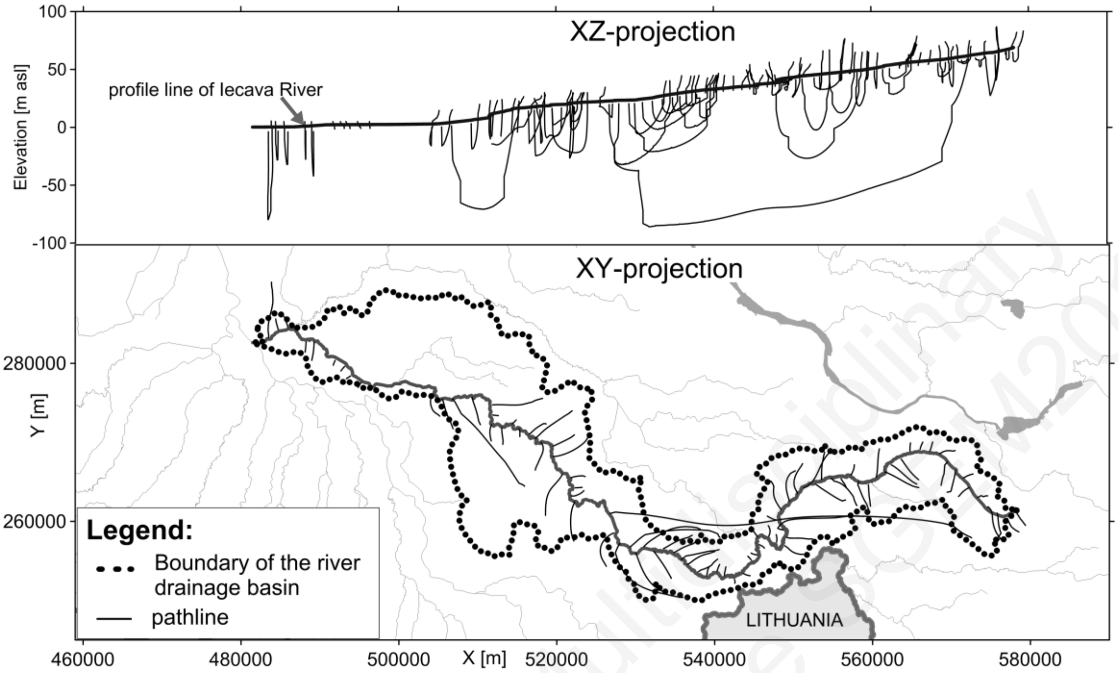

Fig. 9. Display of pathlines of the groups 1., 2., 3., 4.
Only the each tenth pathline in turn is exposed (~80 of 820)

As it follows from the xy- projection of Fig.9, almost all pathlines of the first four groups (maximal time – 1600 years) are located within the river drainage basin. The *xz* – projections of the pathlines confirm the existence of descending and ascending groundwater flows within the basin. This fact can be partly explained by the groundwater flow balance data for the basin (Table 3). Probably, the contrary directed flows ±93 thous.m^3/day for the bottom surface of the aquifer Q may be caused by this feature. The sources for pathlines of the groups 5, 6, 7 are located far outside the river drainage basin. The flow 10 thous.m^3/day for the border of the primary strata may be partly originated by these sources.

It was deduced from data of Fig. 6 that the length of 830 pathlines did not exceed 20 kilometers. The number nearly coincides with the total number (820) of the pathlines which belong to the first four groups of Table 4. Obviously , strong correlation exists between the patline length and the travelling time.

The existence of the long pathlines and opposite vertical flows was discovered due to appliance of the large regional HM, as the driver for the MODPATH system.

The reported results were obtained when a particle was placed in the middle of the HM cell. However, the results depend on the vertical position (top, middle, bottom) of a particle within a cell. It should be found what happens if a group of particles is located within the HM cell. These results can be obtained by the more advanced MODPATH version 6 [7], where the group of particles is used as a unity.

By using MODPATH, new knowledge about the nature processes of groundwater can be gained. For example, very impressive results on geochemical processes were obtained when HM of the eastern part of Lithuania was used as the driver of the MODPATH program [8].

CONCLUSION

The hydrogeological model of Latvia, its current version LAMO4, was used as the driver for the MODPATH program. The attempt was made to find sources of the baseflow of the Iecava river. Unforeseen results were obtained: many sources were located very far from the river drainage basin; even within the basin, the shape of pathlines was very complex. The results of this numerical experiment demonstrate usefulness of applying a large regional HM for investigating the complex processes of nature.

ATCKNOWLEDGEMENTS

In 2010 – 2012, the hydrogeological model of Latvia LAMO1 has been developed within the framework of the RTU project that was co-financed by the European Regional Development Fund. Upgrading of the LAMO3 and LAMO4 versions were supported by the Latvian State Research Program EVIDEnT.

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