

# Creating of Initial Data Maps for Regional Hydrogeological Model of Latvia

Aivars Spalvins<sup>1</sup>, Janis Slangens<sup>2</sup>, Inta Lace<sup>3</sup>, Kaspars Krauklis<sup>4</sup>, Viesturs Skibelis<sup>5</sup>,  
<sup>1-5</sup>Riga Technical University, Environment Modelling Centre

**Abstract** – The hydrogeological model of Latvia will be elaborated in the time period from 2010 to 2012. It will be used for management of groundwater resources of Latvia. The 3D-body to be modeled is represented by 951×601×25 finite difference grid which plane approximation step is 500 metres. The model will be created in the framework of the commercial program Groundwater Vistas, which includes the worldwide used MODFLOW system for running the model. As initial information for creating the model serves a set of digital maps (elevations of geological layer surfaces, permeability of layers, boundary conditions, etc.). Creating maps regarding geometry of the regional model (the digital ground surface map included) is the most difficult task, because geological layers to be modeled are of highly irregular nature. Methods and tools applied for creating initial data maps are described.

**Keywords** – regional hydrogeological model, MODFLOW, digital maps of initial data

## I. INTRODUCTION

The countries of the European Union as well as of the entire world develop hydrogeological models (HM) where, by means of computer modelling, the information necessary for the groundwater management planning is obtained. HM of Latvia will be established, during 2010-2012, by the Environment Modelling Centre (EMC) team of Riga Technical University, as an element of the Latvian shared environmental information system. Detailed information regarding HM of Latvia is given in the publication [1].

To ensure compatibility with models of other countries, the commercial program Groundwater Vistas (GV) is used for running HM [2]. This program is being regularly updated. It contains software tools MODFLOW, MODPATH, MT3D applied for groundwater modeling worldwide.

The model covers 475km×300km area (Fig. 1). It includes Latvia and territories of neighboring countries. For the current HM version, only Latvia and the Gulf of Riga constitute the HM active area because, at present, no agreement exists regarding cross border modelling. However, HM is open for such projects, if a neighboring country provides data for activating the HM area involved.

HM of Latvia includes 25 geological layers (see Fig. 2). Most of them are discontinuous and this results in problems of preparing for GV digital maps of initial data. To understand problems caused by discontinuity, the basic mathematics of the 3D steady model must be introduced. By applying the 3D finite difference approximation, the xyz-grid of HM is built using ( $h \times h \times m$ )-sized blocks ( $h$  is the block plane size,  $m$  is the variable thickness of a geological layer). The model constitutes a rectangular  $p$ -tiered xy-layer system where  $p$  is the number of layers. For HM of Latvia  $p=25$ ,  $h=500$  metres (see Fig. 2). Four vertical sides compose the shell of the HM grid. The relief (ground surface) and the lower side of the model are its geometrical top and bottom, respectively. The 3D-space volume enveloped by the boundary surfaces constitutes the body of HM.

The vector  $\varphi$  of the piezometric head is the numerical solution of the boundary field problem which is approximated in nodes of the HM grid by the following algebraic expression:

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

where  $A$  is the hydraulic conductivity matrix of the geological environment which is presented by the xy-layer system containing horizontal ( $A_{xy}$ - transmissivity) and vertical ( $A_z$  – vertical hydraulic conductivity) elements of the HM grid;  $\psi$  - the boundary head vector,  $G$  – the diagonal matrix (part of  $A$ ) of elements, linking the nodes where  $\varphi$  must be found with the ones where  $\psi$  is given;  $\beta$  - the boundary flow vector. The elements  $a_{xy}$ ,  $a_z$  of  $A_{xy}$ ,  $A_z$  (or  $g_{xy}$ ,  $g_z$  of  $G$ ) are computed, as follows:

$$a_{xy} = k \times m, \quad a_z = (h^2 \times k) / m$$

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

where  $z_{i-1}$ ,  $z_i$  are, elevations, accordingly, of the top and bottom surfaces of the  $i$ -th geological layer;  $z_0 = relh$  is the



Fig. 1: Location of Latvia HM

model upper surface elevation map; *relh* is the hydrogeological relief that includes the hydrographical network; *m*, *k* are, accordingly, elements of digital *m*, *k*-maps of the computed layer thickness and permeability.

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 Šķerveles Ketleru	P2 C1 D3šķ D3ktl	D3ktl#
8.		Ketleru	D3ktl	D3ktlz
9.		Žagares Svētes Tērvetes Mūru	D3žg D3sv D3tr D3mr	D3zg#
10.		Akmenes	D3ak	D3akz
11.		Akmenes Kursas Jonišķu	D3ak D3krs D3jn	D3krs#
12.		Elejas Amulas	D3el D3aml	D3el#z
13.		Stipinu Katlešu Ogres Daugavas	D3stp D3ktl D3og D3dg	D3dg#
14.		Daugavas Salaspils	D3dg D3slp	D3slp#z
15.		Pļaviņu	D3pl	D3pl
16.		Pļaviņu Amatas	D3pl D3am	D3am#z
17.		Amatas	D3am	D3am
18.		Augšējā Gauja	D3gj2	D3gj2z
19.		Augšējā Gauja	D3gj2	D3gj2
20.		Apakšējā Gauja	D3gj1	D3gj1z
21.		Apakšējā Gauja	D3gj1	D3gj1
22.		Burtnieku	D2brt	D2brtz
23.		Burtnieku Arikula Narvas	D2brt D2ar D2nr3	D2ar#
24.		Narvas Narvas	D2nr2 D2nr1	D2nr#z
25.		Pērnavas	D2prn	D2pr

# -united aquifer; #z – united aquitard

 - aquitard

Fig. 2: Vertical schematization

The set of *z*-maps describes the full geometry of HM. For the GV system, only the *z* and *k*-maps serve as the initial data for computing elements of the matrix *A*. The *m*-maps are formed by the GV system internally. Only positive *m* values are allowed, because  $m_i < 0$  values are caused by some errors of the  $z_{i-1}$  and  $z_i$  -maps. If in some areas  $m_i = 0$ , as the known condition, then there *i*-th layer is discontinuous. This publication is devoted to considering problems caused by discontinuity when the elements of the matrix *A* must be obtained. General methods and tools to be used for establishing HM of Latvia are described in [3].

## II. DISCONTINUITY OF MODEL LAYERS

Discontinuity of a geological layer may be caused by its zero thickness beyond its geological borderline (see Fig. 3) or by incisions cut by rivers and buried valleys. Both kinds of discontinuity are present in HM of Latvia.

For discontinuity of the first kind,  $m_i = 0$  must be replaced by  $\varepsilon > 0$  (for HM,  $\varepsilon = 0.02$  metres), to prevent “division by zero” for the  $a_z$  calculation of (2).

It follows from Fig. 3, where the set of geological borderlines is shown that the following problems arise for the  $m=0$  areas:

- for the HM layers  $p=3, 4, \dots, 12$  their zero areas are large and they constitute the tiered “zero body” that covers the existing  $m>0$  layers; to minimize geometrical distortion of the geological space, the thickness  $\varepsilon=0.02$  of layers is used where  $m=0$ ;
- in many places, the distance between the neighboring borderlines does not exceed 1000 metres and there is not enough space to locate between them borderlines of aquitards (not shown in Fig. 3) present there; to overcome this problem, it is assumed that borderlines of the following aquifers and aquitards beneath them coincide: D3ktl# and D3ktlz, D3zg# and D3akz, D3pl and D3amz, D3am and D3gj2z, D3gj2 and D3gj1z, D3gj1 and D2brtz.

To minimize the influence of “zero body” on results of HM, elements  $a_{xy}$  and  $a_z$  must have small and large values, respectively. In HM, the values  $k=1.0\text{m/day}$  and  $m=\varepsilon=0.02$  are applied both for aquifers and aquitards. Formula (2) gives  $a_{xy}=0.02\text{m}^2/\text{day}$  and  $a_z=12.5 \times 10^6\text{m}^2/\text{day}$ . Even if “zero body” contains ten planes, its total vertical conductivity  $a_z/10=1.25 \times 10^6\text{m}^2/\text{day}$  has no real influence on results given by HM.

Although buried valleys may be of considerable local importance, they are not accounted for in the current version of HM. It is rather difficult to incorporate them properly into the body of HM for geometrical reasons and their filling material may be unknown.

In the next section accounting for valleys of rivers is considered as a part of obtaining the Quaternary system thickness.

## III. THE QUATERNARY SYSTEM THICKNESS

Formally, the thickness  $m_Q$  of the Quaternary system (planes 2, 3, 4, 5, 6 of HM), is the following difference:

$$\Delta_Q = relg - sub_Q \quad (3)$$

where the elevation surfaces  $relg = z_1$  and  $sub_Q = z_0$  represent, accordingly, the geological relief as the ground surface (Fig. 4) and the sub Quaternary surface (Fig. 5).

It follows from Fig. 6 where the  $m_Q$  map is shown that  $\Delta_Q < 0$ , along walleys of rivers Abava, Gauja, Daugava, Venta and the other ones. It means that the  $sub_Q$ -map does not account for valleys of these rivers. However, no attempt has been made to correct the map by deepening its surface along the river valleys, otherwise, the grid nodes will be lost where the GV system must connect elements joining river elevation values with a HM layer and there the GV option River will be unable. For this reason, at areas where  $\Delta_Q < 0$ , the HM body remains unchanged. To ease problems of creating surfaces  $z_2, z_3, z_4, z_5$  for the Q system, it is assumed that  $m_Q \geq 1.0$ .

By accounting for the above considerations, the difference  $\Delta_Q$  of (3) is used for obtaining the thickness  $m_Q$ , as follows:

$$m_Q = \Delta_Q, \text{ if } \Delta_Q \geq 1.0; \\ m_Q = 1.0, \text{ if } \Delta_Q < 1.0, \text{ then } relg = z_0 - 0.02; z_0 = sub_Q + 1.02, \quad (4)$$

where if  $m_Q = 1.0$ , values of  $z_0$  and  $relg$  are changed; the value  $m_Q = 1.0$  is sufficient for linking of a river with the Q system.

The thickness  $m_{rel}$  of the first HM plane where the boundary condition  $\psi_{rel} = relh + 0.02$  is set, is computed, as follows:

$$m_{rel} = 0.02 + m_w = relh - relg = z_0 - z_1 \quad (5)$$

where  $m_w$  is the thickness of surface water bodies (in HM, the sea area and the Daugava river with three lakes of hydroelectrical power stations of Plavinas, Kegums, Riga). If  $m_w = 0$ , then  $m_{rel} = 0.02$ .

The condition  $\psi_{rel} > z_0$  eliminates warnings of GV when all layers of HM are used in the confined mode. The variable thickness  $m_{rel}$  enables to include  $m_w > 0$  into the HM body.

If not bog areas, the initial thickness of the aeration zone  $m_{aer} = 0.02 = z_1 - z_2$ . If the bog thickness is known, it is also used as initial  $m_{aer}$  that is fixed during HM calibration. The real thickness  $m_{aer}$ , as the upper part of the Q system, can be restored by using methods described in [3].

#### IV. INTERPOLATION TOOLS

Interpolation surfaces of the k, z-maps represent geometrical images. They include various lines which are carriers of initial data (geological borderlines, long lines of rivers, coastlines of lakes, isoline data and others). The commonly applied SURFER system [4] uses pointwise data mainly and it does not provide interpolation tools that account for data lines. For this reason, the EMC team applies SURFER only for sorting initial pointwise data when their errors must be eliminated. This system cannot create the final version of the k, z-maps of HM, because various data lines are the main source of initial information for the model.

The EMC team has developed the geological data interpolation (GDI) program that applies both pointwise and line data. This program can create any digital data map of HM of Latvia. A brief history of the GDI development is given below.

In 1994, EMC team managed to apply widely known interpolation methods of SURFER: Criging, Minimal Curvature, Inverse Distance. Unluckily, these methods sometimes provided evidently wrong results [5]. For example, if an m-distribution was highly irregular, negative thicknesses appeared, even if the initial ones were strictly positive. It was understood that this unexpected failure was due to the following principal hindrances of these methods:

- interpolated results did not hold the maximum / minimum principle towards initial data applied;
- initial data were often overruled by practically uncontrollable algorithms applied for smoothing of the interpolation result.

Because conventional methods cannot provide strictly controllable interpolation results, the GDI program has been developed [5, 6, 7]. It provides the interpolation surface  $\sigma$ , as the numerical solution of the following associated 2D – boundary problem, on the i–th plane of system (1):

$$\text{div}(\lambda \text{grad } \sigma) = 0, \quad (6)$$

$$V \sigma = -G_\sigma \sigma_\psi, \quad V = V_{xy} - G_\sigma \quad (7)$$

where (7) is the algebraic equation system, applied to approximate the problem (6); the matrices  $V_{xy}$ ,  $G_\sigma$  represent, correspondingly, the horizontal links  $V_{xy}$  of the interpolation grid and the elements  $g_\sigma$  connecting nodes where  $\sigma$  must be found with the ones where  $\sigma_\psi$  are known. The parameter  $\lambda(x,y)$  is used for controlling the shape of  $\sigma(x,y)$ . Due to the changeable  $\lambda(x,y)$ , it is possible to modify the « strength » for each initial data source  $\sigma_\psi$ .

The GDI program mostly applies various line data as the initial ones, because they are much more informative than few pointwise data on which the lines are based on. For example, information carried by the long line profile of a river is far richer than the measured water levels of the river applied for obtaining the profile.

In GDI, if necessary, any line can also be used, as an impervious border that dissects the xy–area, (masking of polygons, tectonic faults etc.).

An original program CRP has been developed for preparing the line data (isolines, geological borderlines, data of hydrographical network) and converting them into the initial data  $\sigma_\psi$  of the GDI program [8].

The GDI program is mainly applied in the sequential mode. During the current interpolation step, new information is used, but the results of the previous step serve, as the base. In this way, much simpler set of initial data can be applied than if one tries to obtain the final result at once. To create very complex maps, even small sets of initial root data are sufficient.

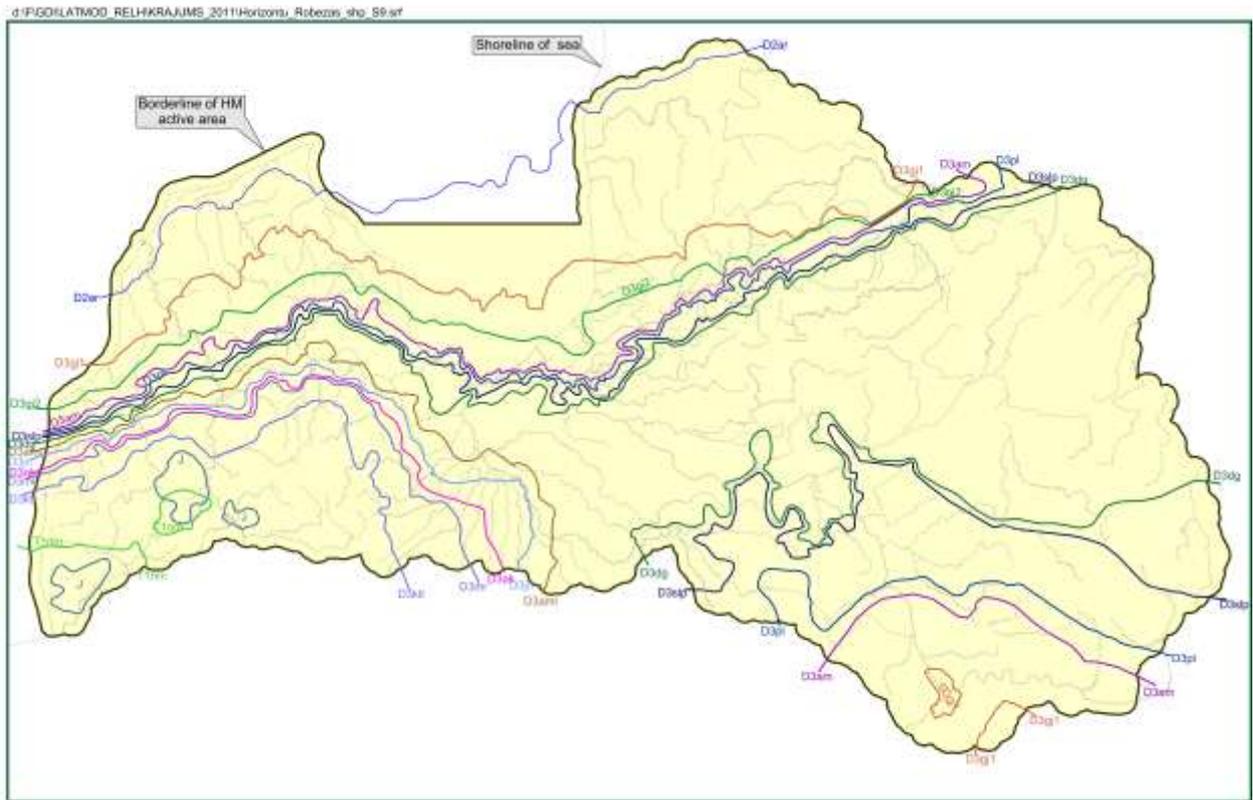


Fig. 3. The set of geological borderlines

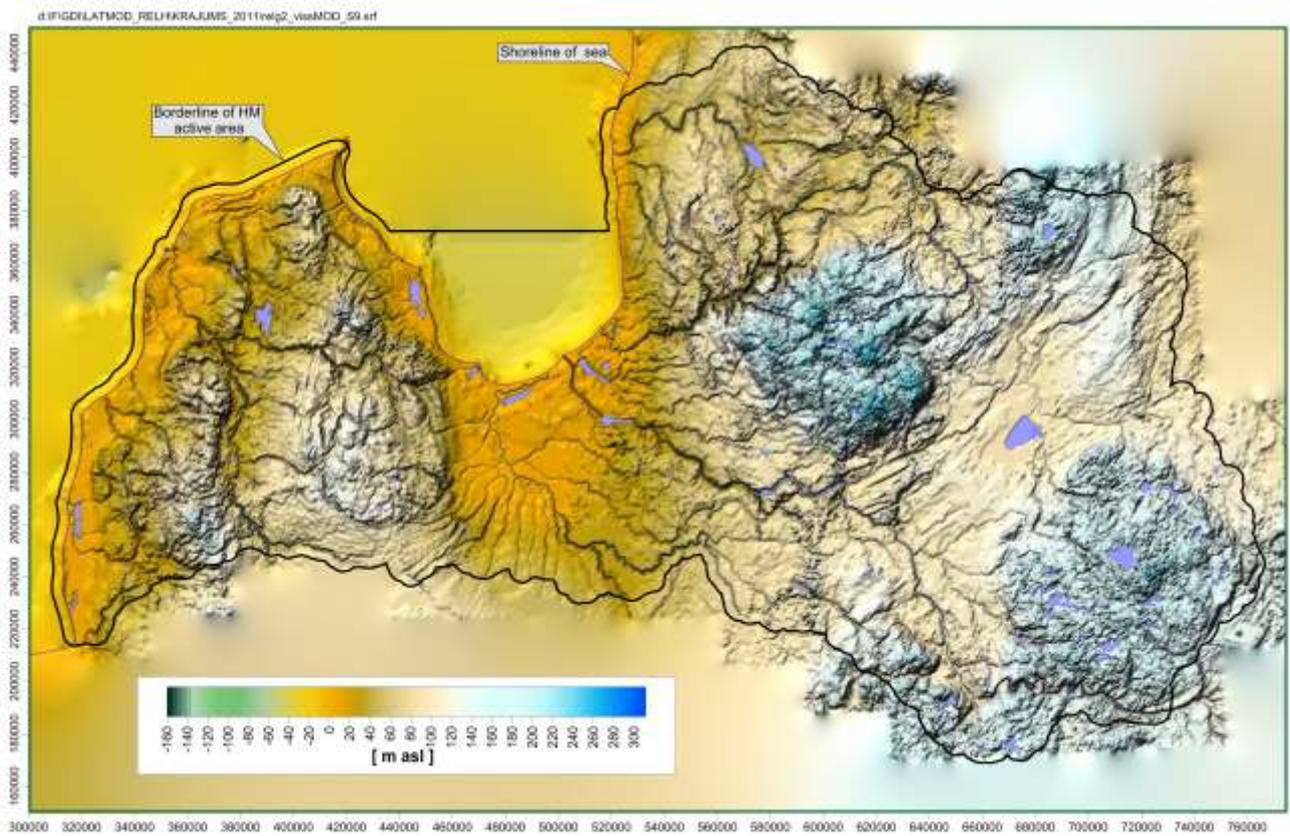


Fig. 4. The geological relief *relg* elevation map [m asl]

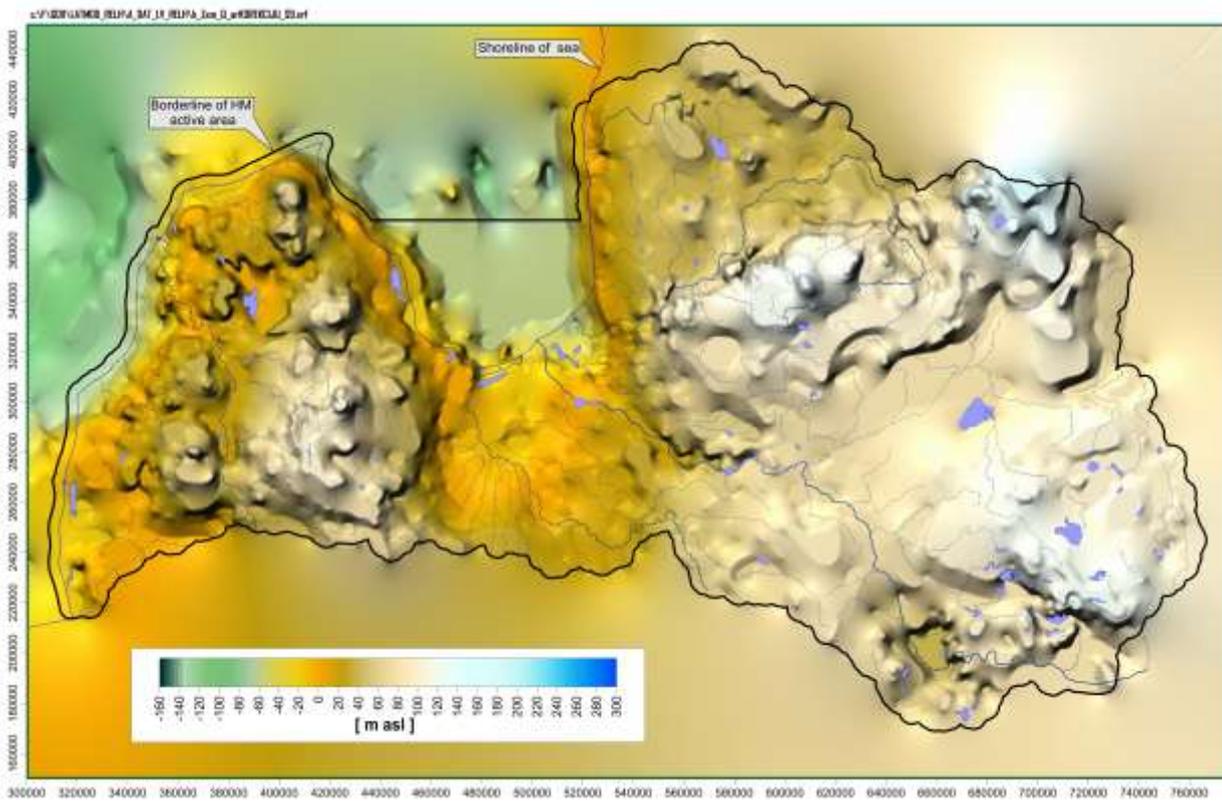


Fig. 5. The sub Quaternary surface  $sub_Q$  elevation map [m asl]

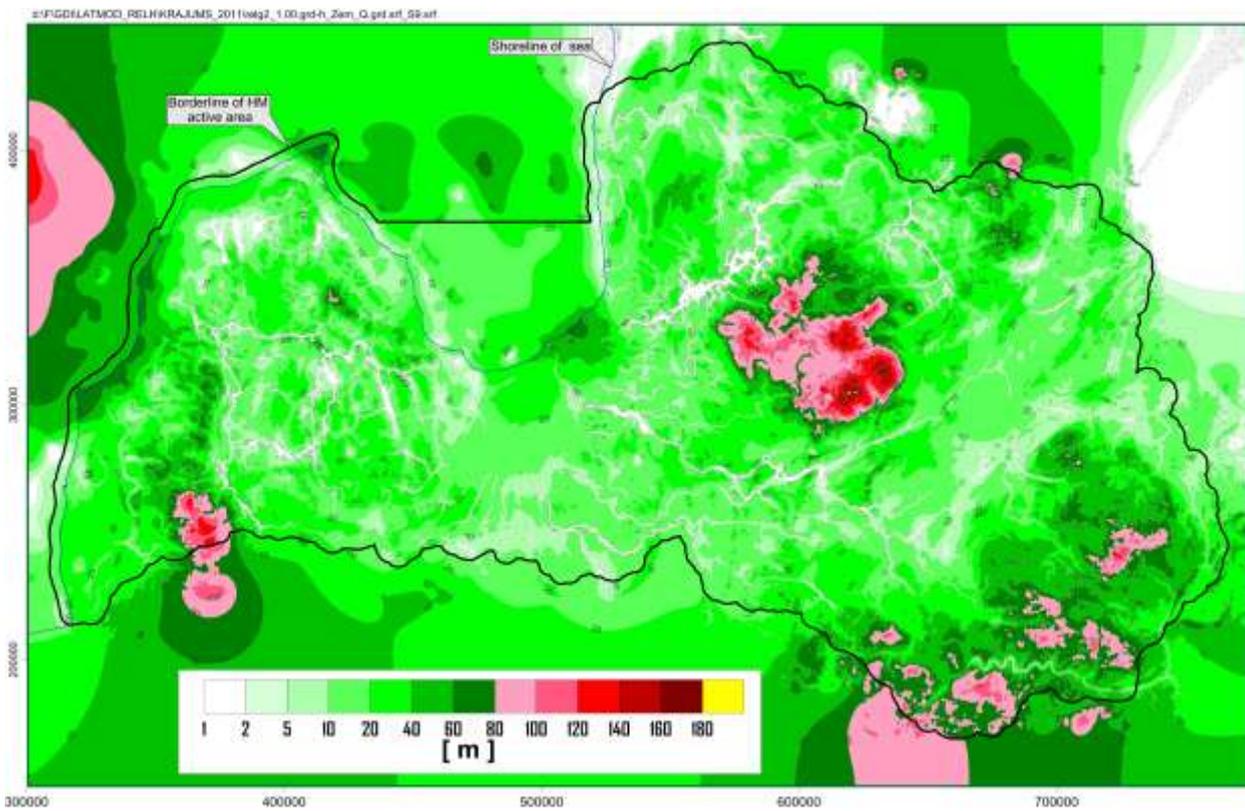


Fig. 6. The Quaternary system thickness  $m_Q$  map [m]. For the white colored areas,  $m_Q = 1.0$

Unlike most interpolation methods, the surface created by GDI may include sharp edges that are very often a part of the z-maps (river valleys, tectonic faults, etc.).

As examples of the GDI products prepared for HM of Latvia, two maps presented by Fig. 4 and Fig. 5 are considered. Both maps are created for the whole HM area. However, they are accurate only within the active HM area. Their data, located outside this area, are ignored by the GV system, because they belong to the HM passive part.

The map of Fig. 4 illustrates ground surface elevations and this part of hydrographical network (rivers as lines and lakes as areas) where, conditionally,  $m_w=0$ .

As the main source of initial data, vectored topographical maps of the scale 1:50000 were used where elevation data were presented by isolines. This set of maps has been prepared by the Geospatial Information Agency of Latvia. It was necessary to find and correct isoline errors [9]. From these corrected data, by using special methods, long lines of rivers, elevations and contours of lakes were obtained [10], as the hydrographical network elements, which should also be used by the GV options Rivers and Lakes.

To obtain the *relg* map, two sequential GDI steps were performed:

- by using elevation isolines, the ground surface base was obtained which did not represent rivers and lakes satisfactory;
- by implementing into the base surface map the hydrographical network, the final *relg* map was obtained.

The first version of the map of Fig.5 was prepared by the Latvian Environment, Geology and Meteorology Centre. This map was corrected by the EMC team, in order to eliminate evidently false areas where  $\Delta\varrho < 0$ . This map was obtained by GDI when elevation isolines and some pointwise data were used.

The GDI program also enables to keep the small thickness 0.02 within the areas where  $m=0$  (discontinuous layers).

## V. CONCLUSIONS

During two years (till 2012), the EMC team of Riga Technical University should establish the regional hydrogeological model of Latvia. To create the model, serious problems must be solved regarding discontinuity of geological layers. This factor makes more difficult the task of creating digital maps which carry initial data necessary for running the Groundwater Vistas modeling system. It is shown, how discontinuity of layers is accounted for. The digital maps for creating the model are obtained by the Geological Data Interpolation program which has been developed by the EMC team.

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**Aivars Spalvins** was born in 1940, Latvia. In 1963, he graduated from Riga Polytechnical institute (since 1990, Riga Technical University) as a computer science engineer. In 1967, A. Spalvins received the degree of Candidate in Technical Sciences.

A. Spalvins has been with the University since 1958.. His present scientific interests are computer modelling of groundwater flows and migration of contaminants. He is the author of about 300 scientific papers. His present position is the Head of Environment Modelling Centre of Riga Technical University.

He is a member of the International Association of Hydrogeologists.

Address: 1/4 Meza str., Riga, LV-1007, Latvia

Phone: +371 67089511

E-mail: [emc@cs.rtu.lv](mailto:emc@cs.rtu.lv)

**Janis Slangens** was born in 1940, Latvia. In 1969, he graduated from Riga Polytechnical institute (since 1990, Riga Technical University) as computer science engineer. In 1985, J. Slangens received the degree of Candidate in Technical Sciences.

Since 1969, he has been a lecturer at the Department of Computer Engineering of the Faculty of Computer Science and Information Technology. Since 1993, he has been a senior researcher at the Environment Modelling Centre. His present scientific interests are computer modelling of groundwater flows. He is the author of about 200 scientific papers.

Address: 1/4 Meza str., Riga, LV-1007, Latvia

Phone: +371 67089511

E-mail: [emc@cs.rtu.lv](mailto:emc@cs.rtu.lv)

**Inta Lace** was born in Latvia. In 1971, she graduated from Riga Polytechnical institute (since 1990, Riga Technical University) as a computer science engineer. In 1995, I. Lace received the degree of M.sc. (applied computer science).

I. Lace has been with the university since 1965. Since 1991, she is a researcher at Environment Modelling Centre of the Faculty of Computer Science and Information Technology at Riga Technical University. She took part in the projects of Latvian Council of Science on informatics for hydrogeology and other projects. Her present scientific interests are computer modelling of groundwater flows. She is the author and co-author of about 100 scientific papers on software used for solving boundary field problems.

Address: 1/4 Meza str., Riga, LV-1007, Latvia  
Phone: +371 67089511  
E-mail: emc@cs.rtu.lv

**Kaspars Krauklis** holds the degree of M.Sc. (engineering science in computer systems) from Riga Technical University (2007) and the Certificate in Teaching of Engineering Sciences from RTU Institute of Humanities (2005). Since 2005, he participated in several projects of ESF, ERDF and Latvian Council of Science. Since 2007, he is a PhD student of RTU at the Faculty of Computer Science and Information Technology. Currently he works as a researcher at the Environment Modelling Centre which is a part of the Faculty of Computer Science and Information Technology of Riga Technical University and as a lecturer in the Department of Applied Systems Software of RTU. His main scientific interests are -

groundwater modelling and technologies of e-learning. He is the author and co-author of 17 publications in both above mentioned fields.

Address: 1/4 Meza str., Riga, LV-1007, Latvia  
Phone: +371 67089511  
E-mail: [emc@cs.rtu.lv](mailto:emc@cs.rtu.lv)

**Viesturs Skibelis** was born in 1945, Germany. In 1967, he graduated from Riga Polytechnical institute (since 1990, Riga Technical University) as a computer science engineer. In 2001, V. Skibelis received the degree of M.sc. (applied computer science).

V. Skibelis has been with the university since 1965. Since 1971, he is a researcher of Environment Modelling Centre at the Faculty of Computer Science and Information Technology of Riga Technical University. Since 1991, he took part in projects of Latvian Council of Science on informatics for hydrogeology and other projects. His present scientific interests are computer modelling of groundwater flows and diagnostic of electrical circuits. He is the author and co-author of about 30 scientific papers.

Address: 1/4 Meza str., Riga, LV-1007, Latvia  
Phone: +371 67089511  
E-mail: [Viesturs.Skibelis@cs.rtu.lv](mailto:Viesturs.Skibelis@cs.rtu.lv)

#### **Aivars Spalviņš, Jānis Šlangens, Inta Lāce, Kaspars Krauklis, Viesturs Šķibelis. Sākuma datu karšu iegūšana Latvijas reģionālajam hidrogeoloģiskajam modelim**

Latvijas reģionālais hidrogeoloģiskais modelis tiks izveidots laikā no 2010. gada līdz 2012. gadam, kā Eiropas Reģionālā attīstības fonda līdzfinansēts projekts. Modeli izmantos Latvijas pazemes dzeramā ūdens krājumu pārvaldībai un to pasākumu novērtēšanai, kuri tiek īstenoti šo resursu saglabāšanai. Modelis būs publiski pieejama daļa Latvijas Vides informācijas sistēmā. Telpiskā modeļa vide tiek aproksimēta ar galīgo starptību režģi, kura izmērs ir  $951 \times 601 \times 25$ . Režģa plaknes solis ir 500 metri. Modelī realizēti ģeoloģiskie slāņi, kuri atbilst Latvijas aktīvo pazemes ūdeņu zonai. Šo zonu izmanto dzeramā ūdens iegūšanai (līdz Narvas sprostslānim). Modelis tiks īstenots sistēmas Groundwater Vistas vidē, kurā ietvertas speciālas modelējošas programmas (MODFLOW, MODPATH, MT3D), kuras tiek plaši izmantotas pasaulē un Latvijā. Kā sākuma informācija modeļa veidošanai kalpo digitālo karšu kopa (ģeoloģisko slāņu virsmu augstumi, slāņu filtrācijas īpašības, robežnoteikumi u.c.). Vislielākās problēmas rada to karšu izveidošana, kuras nosaka modeļa ģeometriju, īpaši Latvijas digitālās reljefa kartes izveidošana. Modelī iekļautie ģeoloģiskie slāņi nav nepārtraukti un šis apstāklis rada specifiskas problēmas šādu slāņu virsmas augstumu karšu izveidošanā. Rakstā apskatītas metodes un programmatūras rīki, kuri tiek izmantoti sākuma datu karšu izveidošanai Latvijas hidrogeoloģiskajam modelim.

#### **Айварс Спалвиньш, Янис Шлангенс, Инта Ляце, Каспарс Крауклис, Виестурс Шкибелис. Создание карт исходных данных для региональной гидрогеологической модели Латвии**

Гидрогеологическая региональная модель Латвии будет создана Рижским Техническим университетом с 2010 до 2012 года как проект Регионального фонда развития Европы. Модель будет использована для осуществления управления ресурсами подземной питьевой воды Латвии, а также для оценки мер по сохранению этих ресурсов. Модель будет публично доступна как часть информационной системы Латвии по окружающей среде. Объемная среда модели будет представлена конечно-разностной сеткой размером  $951 \times 601 \times 25$ . Плоскостной шаг сетки равен 500 метрам. Модель содержит 25 геологических горизонтов, которые представляют активную зону подземных вод Латвии (до Нарвского водоупора). Эта зона используется как источник питьевой воды. Модель будет реализована в среде системы Groundwater Vistas, которая содержит широко используемые в мировой практике специальные моделирующие программы (MODFLOW, MODPATH, MT3D). Как исходная информация для построения модели служит множество цифровых карт (высота поверхностей геологических структур, свойства фильтрации среды, граничные условия и другие). Значительные проблемы необходимо преодолеть по созданию карт геометрии модели, особенно карты цифрового рельефа Латвии. Геологические горизонты не являются непрерывными, и этот фактор значительно усложняет процесс создания карт поверхностей таких горизонтов. В статье рассмотрены методы и программные средства, которые применяются для создания гидрогеологической модели Латвии.