

## THE NEW METHOD FOR FINDING BORDERS OF GROUNDWATER RECHARGE, TRANSIT AND DISCHARGE AREAS

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### ABSTRACT

Hydrogeologists are interested in borders that separate the groundwater recharge, transit, discharge (RTD) areas. Unfortunately, no good method exists for finding them. In the course of using the hydrogeological model (HM) of Latvia (LAMO) scientists of Riga Technical University have developed the new method that generalizes the RTD concept and gives locations of the borders. LAMO is run by the commercial program Groundwater Vistas (GV). The GV program provides the velocities  $v_z$  for the vertical and  $v_x$ ,  $v_y$  for the horizontal groundwater flows. These velocities are used to create the function  $r$  for describing the borderlines of the RTD areas. The function  $r$  originates the four areas: R, positive T (+T), negative T (-T), D. The value  $r = 0$  denotes the border that separates the +T and -T areas. The values  $r = 1$ ;  $r = -1$  depict the borders between the R, and +T; -T and D areas, correspondingly. The new method will be applied for investigating the regional groundwater processes that are modelled by LAMO.

**Keywords:** hydrogeological modelling, recharge, transit and discharge areas, velocity of groundwater flow

### INTRODUCTION

LAMO was developed to obtain the information necessary for groundwater management and for environment protection. The current version LAMO4 [1] covers the area  $475\text{km} \times 300\text{km} = 142.5$  thous. $\text{km}^2$  (see Fig. 1.). Its active part (71.3 thous. $\text{km}^2$ ) includes the land territory of Latvia, the Gulf of Riga and 27 geological layers (Fig. 2.).



Fig. 1. Location of LAMO4.

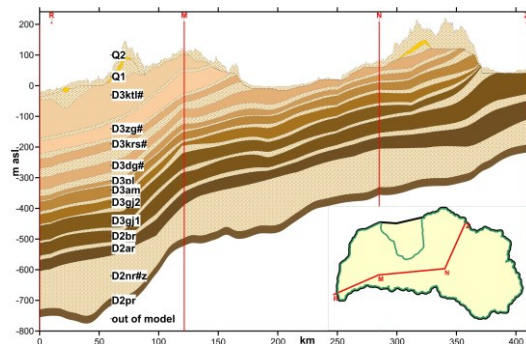


Fig. 2. Geological cross section R-M-N-Z

The commercial program Groundwater Vistas (GV) [2] is used for running LAMO4. The GV program contains the worldwide applied systems: MODFLOW (supports HM) [3], MODPATH (particle tracking) [4], MT3D (mass transport) [5].

By using the finite difference method [6], the xyz-grid of HM is built. The grid contains  $1900 \times 1200 \times 27 = 61.56 \times 10^6$  blocks of the size  $(h \times h \times m)$ ;  $h=250$  metres is the plane approximation step of LAMO4;  $m$  is the variable thickness of a geological layer. In Fig. 3, the HM block  $h \times h \times m_i$  for the  $i$ -th layer is shown. The thickness  $m_i$  [metre] for the layer is computed ( $m$ -maps) by GV itself, as follows:

$$m_i = z_i - z_{i+1} > 0, \quad z_{i+0.5} = 0.5(z_i + z_{i+1}), \quad i=1, 2, \dots, p \quad (1)$$

where  $z_{i-1}$  and  $z_i$  are, accordingly, the elevations [m asl] of the top and bottom surfaces of the  $i$ -th geological layer;  $z_1$  is the ground surface; for LAMO4  $p = 27$  is the number of layers; there are  $p+1=28$  surfaces (the set of  $z$ -maps) that determine the HM geometry (stratigraphy). For discontinuous layers, the  $m=0$  areas exist; for LAMO4, to avoid division by zero,  $m=0.02$  metre is used there; the nodes of the xyz-grid are located on the surface  $z_{i+0.5}$ .

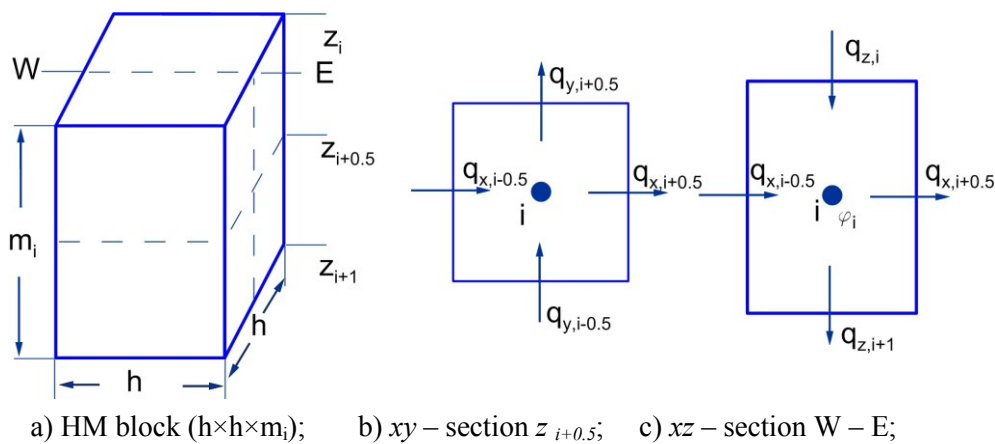


Fig. 3. Lateral (transit) and vertical (recharge, discharge) groundwater flows  
for the HM block ( $h \times h \times m_i$ )

The set of digital  $k$ -maps determines permeability  $k$  [metre/day] of geological layers. There are two types of the layers that differ in the values of  $k$ : aquifers ( $k=1-50$ ) and aquitards ( $k=10^{-2}-10^{-6}$ ).

Only the aquifers can serve as sources for obtaining drinking water. Due to the aquitards, the groundwater system is spatial.

HM provides the values  $\phi$  [m asl] of the piezometric groundwater levels in each node of the xyz-grid ( $\phi$ -maps) and the set of the groundwater flows ( $q$ -maps) that intersect the surfaces of the HM grid blocks.

For investigating the problem of finding the borders for the RTD areas, the set of the  $q$ -maps is the most important one.

## THE LATERAL AND VERTICAL GROUNDWATER FLOWS

Two types of groundwater flows are computed by HM (Fig. 3.):

- lateral flows  $q_x, q_y$  that intersect the four sides of the grid block; they represent the sidewise motion (transfer) of water (see Fig. 3b.);
- vertical flows  $q_z$  that intersect the top and bottom surfaces ( $z_i$  and  $z_{i+1}$ ) of the  $i$ -th block (see Fig. 3c). Vertical flows recharge/discharge the groundwater resources; it is done, accordingly, by the downward (positive)/upward (negative) flows.

For the  $i$ -th block, the GV system computes the entrance flows  $q_{x,i-0.5}$ ,  $q_{y,i-0.5}$  and  $q_{z,i}$  that intersect, accordingly, the two front sides ( $h \times m_i$ ) and the top surface  $z_i$  ( $h \times h$ ) of the block. The exit flows  $q_{x,i+0.5}$ ,  $q_{y,i+0.5}$  and  $q_{z,i+1}$  are the entrance flows of the neighbouring blocks.

To run the MODPATH program, the GV system provides the velocities  $v_x$ ,  $v_y$  and  $v_z$  of the entrance flows:

$$v_{x,i-0.5} = q_{x,i-0.5} / (h m_i), \quad v_{y,i-0.5} = q_{y,i-0.5} / (h m_i), \quad v_{z,i} = q_{z,i} / h^2. \quad (2)$$

To investigate the RTD problem, the velocities  $v_{z,i}$  and  $v_{z,i+1}$  are used and the module of the velocity  $v_{xy,i}$  of the resulting lateral flow is computed:

$$v_{xy,i} = ((v_{x,i-0.5h})^2 + (v_{y,i-0.5h})^2)^{1/2} = k_i \text{ grad } \varphi_i \quad (3)$$

where the more exact method applies permeability  $k_i$  and the grad  $\varphi_i$  that is computed by SURFER [7] on the  $2h \times 2h$  area..

It follows from [8, 9] that  $q_{xy} \sim 0$  for aquitards and also for the aquifers if their  $m=0$ . For these geological layers, only the R and D areas exist, because  $v_{z,i} \sim v_{z,i+1}$ .

## THE ORDINARY METHOD FOR FINDING THE RTD AREAS

Hydrogeologists intuitively locate the R and D areas, correspondingly, with uplands where the precipitation infiltrates into the groundwater body and with lowlands, rivers and lakes where groundwater exits from the underground. The infiltration  $inf$  [mm/year] is obtained, as follows:

$$inf_i = v_{z,i} \times 365 \times 10^3, \quad (4)$$

where  $v_{z,i}$  [metre/day] is the velocity of the vertical flow on the ground surface. For the  $i$ -th aquifer, the velocity  $v_{z,i}$  is used, to obtain its infiltration map  $inf_i$ . In Fig. 4, the infiltration map is shown for the D2ar aquifer (25-th layer) of LAMO4.

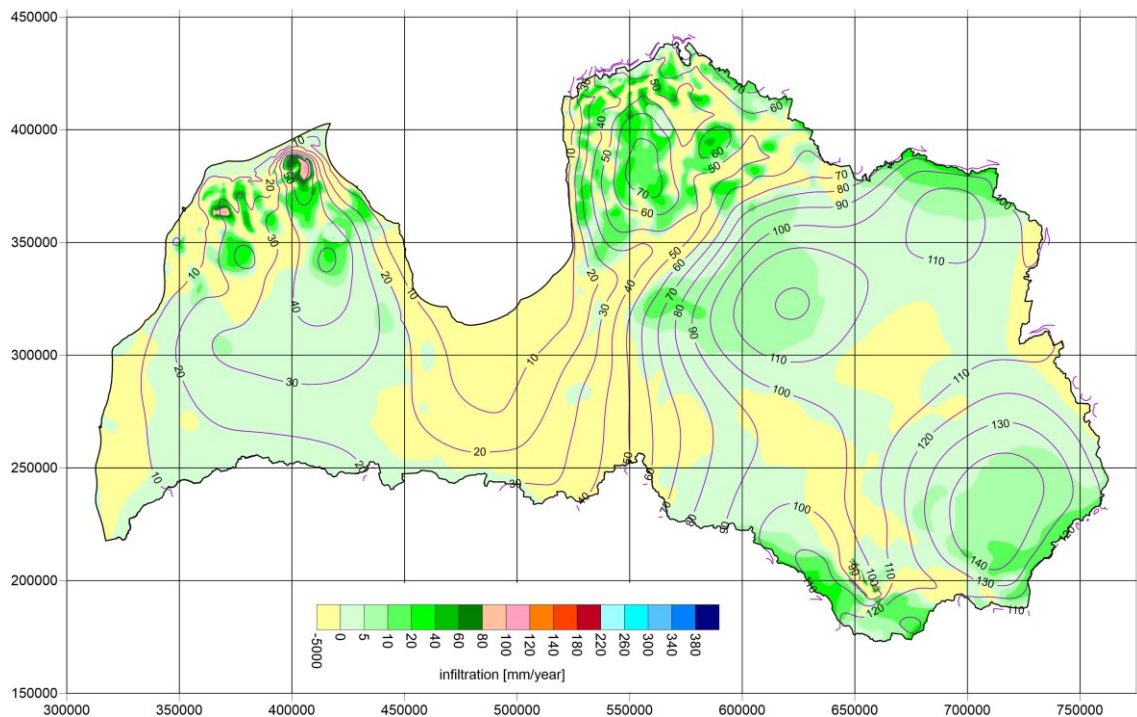


Fig. 4. The infiltration and the  $\phi$  – distribution for the D2ar aquifer (25-th layer) of LAMO

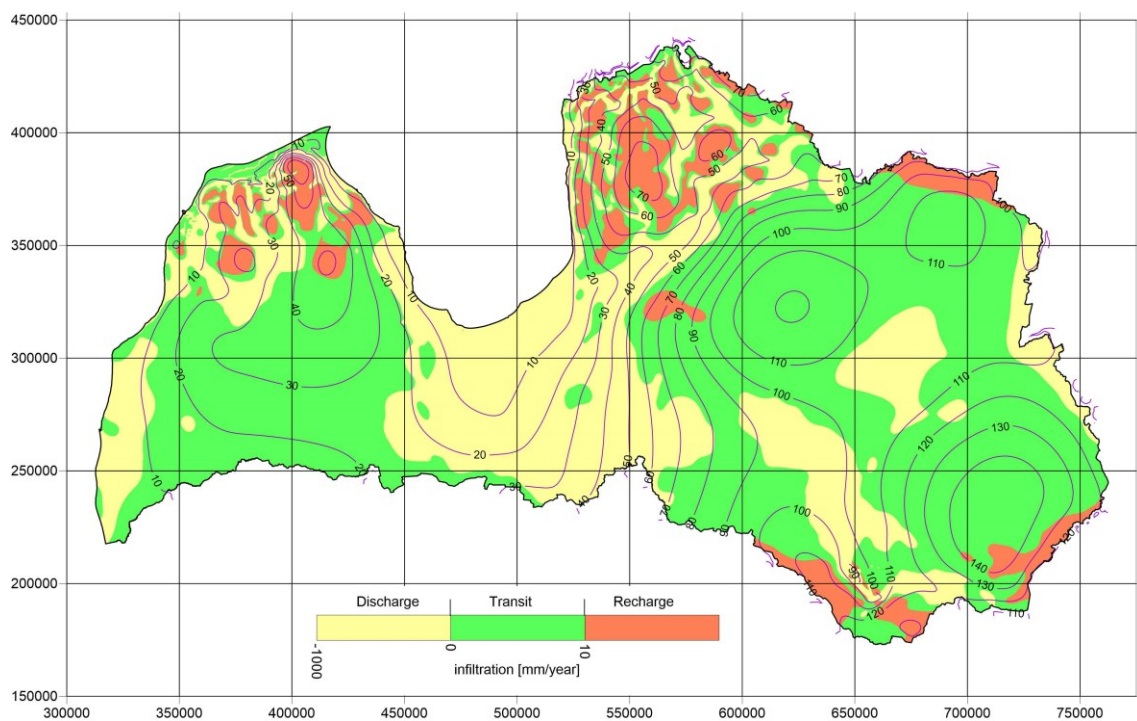


Fig.5. The R, T, D areas that are obtained by the ordinary method for the D2ar aquifer

It follows from the infiltration map that the borderline  $v_z=0$  separates the areas where  $v_z > 0$  and  $v_z < 0$ . Within both areas, the vertical and lateral flows exist simultaneously. Unfortunately, no good method is known for finding the borderlines that separate the R and D areas from the T ones. To obtain the RTD areas for the LAMO2 version [10], the simple ordinary method was used (see Fig. 5.). Conditionally, it was assumed that for the D2ar aquifer, the infiltration threshold  $inf=10$  mm/year denotes the location of the borderline that separates the R and T areas.

For the D2ar aquifer, the method failed to find the all R areas, because they definitely existed at the places where the  $\varphi$ -maximums were present (see Fig. 5.). The failure was caused by the large difference of recharge flows at various areas of the aquifer. The flows were much larger in the northern part of the D2ar aquifer due its closeness to the ground surface. The other serious defect of the method was the necessity to define the different infiltration threshold for each aquifer.

### THE NEW METHOD FOR FINDING THE R, T, D AREAS

The new method for finding borders for the R, T, D areas of the  $i$ -th aquifer applies the velocities  $v_{z,i}$ ,  $v_{z,i+1}$ ,  $v_{xy,i}$  as the ratio  $r_i$ :

$$r_i = c_1 \frac{v_{z,i}}{v_{xy,i}}, \quad r_i = c_2 \frac{0.5(v_{z,i} + v_{z,i+1})}{v_{xy,i}}, \quad r_i = c_3 \frac{v_{z,i} - v_{z,i+1}}{v_{xy,i}} \quad (5)$$

where  $r_i$  is the dimensionless function;  $c_1$ ,  $c_2$ ,  $c_3$  are the dimensionless empiric constants for three flow type cases.

The first and the second cases are the sole and mean transportation flows, correspondingly. These flows represent the vertical transport of groundwater. The third case is related to the consumption flow when the mass balance of the aquifer is considered.

The function  $r$  originates the four areas: R, positive T (+T), negative T (-T), D:

$$R (r > 1); \quad +T (1 > r > 0); \quad -T (0 > r > -1); \quad D (-1 > r). \quad (6)$$

The value  $r=0$  denotes the border that separates the +T and -T areas; the values  $r=1$ ;  $r=-1$  depict the borders between the R and +T, -T and D areas, accordingly. The location of these borders can be controlled by changing the empiric constant  $c$  of (5).

#### The transportation flow case

For the  $i$ -th aquifer, the velocities  $v_{z,i}$  and  $v_{z,i+1}$  of the vertical entrance and exit flows are not equal. On the surface  $z_{i+0.5}$ , their mean velocity  $0.5(v_{z,i} + v_{z,i+1})$  exists. The first case is preferable when in (5) the entrance velocity  $v_{z,i}$  is applied, because then the location of the borderline  $r=0$  coincides with the one on the infiltration map.

For aquifers,  $v_{xy,i} > |v_{z,i}|$ . For this reason, to create the function  $r_i$ , the empiric constant  $c_1$  must be large enough for developing the RTD areas. If  $c_1=1$  then for the D2ar aquifer, the R and D areas exist only as points and lines where, accordingly,  $r=1$  and  $r=-1$ . If  $c_1=180$  then the borderlines  $r=1$  roughly match the shapes of  $\varphi$  – isolines at places of their maximums in Fig.5. In Fig. 6., the R, T, D areas for the D2ar aquifer are shown if  $c_1=180$ .

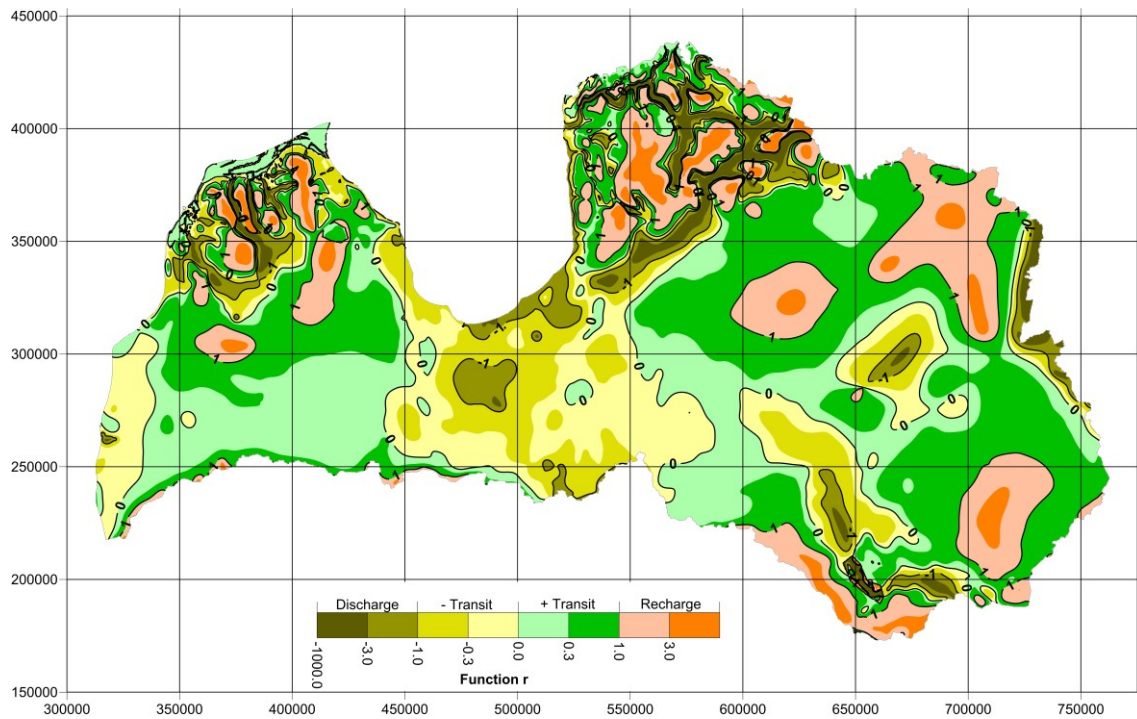


Fig. 6. The R, T, D areas for the D2ar aquifer; the sole transportation flow case

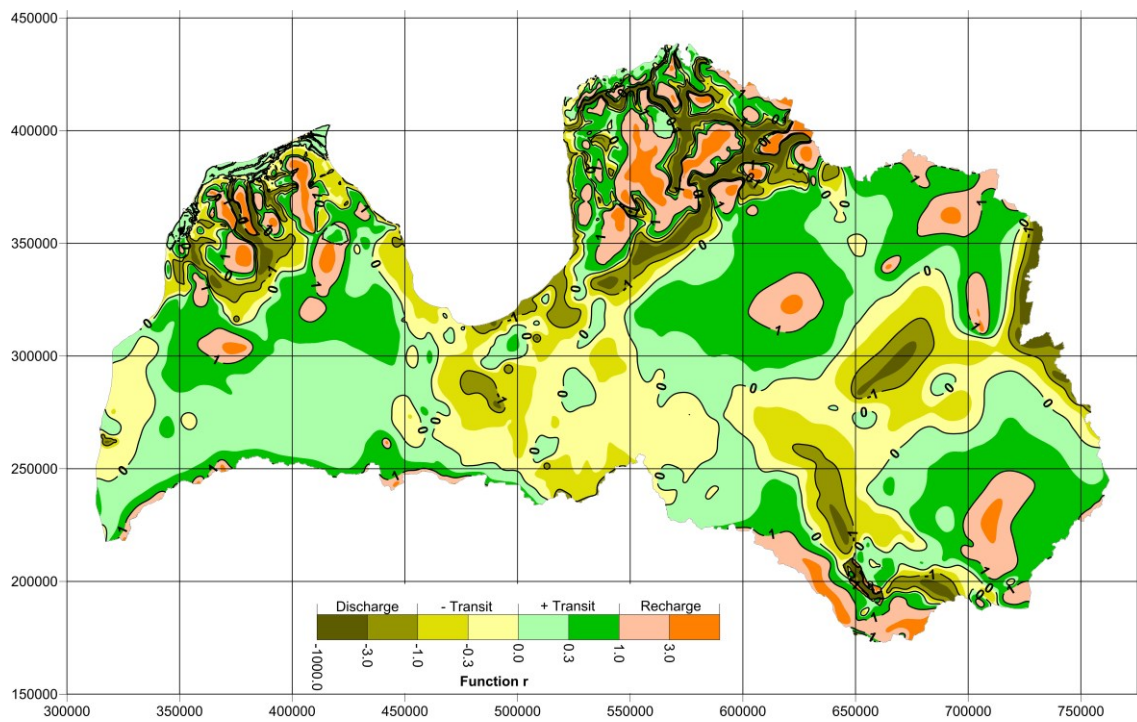


Fig. 7. The R, T, D areas for the D2ar aquifer; the consumption flow case

Presently, no justified motivation on the choice of the empiric constant  $c$  is known. However, due to appliance of the function  $r$ , the locations of the borderlines  $r = \pm 1$  are found for the R and D areas and the +T and -T areas are also marked. Due to making use of the colour scale, one can notice that the function  $r$  changes within the R, T, D areas. Its maximal/minimal values correspond, accordingly, with the R/D areas.

If the mean transportation flow case is considered when  $v_z = 0.5(v_{z,i} + v_{z,i+1})$ , the location of borderline  $r = 0$  will not coincide with the one on the infiltration map of Fig. 4.

### The consumption flow case

The consumption flow is used when the groundwater flow balance for an aquifer and also for a larger groundwater system must be computed. In this case, the difference  $\Delta q_z = q_{z,i} - q_{z,i+1}$  is the flow consumed by the  $i$ -th block of the aquifer. For this reason, the resulting velocity of the vertical flow  $v_z = v_{z,i} - v_{z,i+1}$  is used for computing the function  $r$ .

In Fig. 7., the R, T, D areas for the D2ar aquifer are shown, if  $c_3 = 180$ . The value  $c_I = c_3 = 180$  was used, in order to fix influence of the first part  $v_{z,i}$  in the formula  $v_{z,i} - v_{z,i+1}$ . Then it is possible to understand changes of the function  $r$  that are caused by the second part  $v_{z,i+1}$ .

In general, the images of the R, T, D areas are similar for the cases of sole transportation and consumption flows (compare Fig. 6. with Fig. 7.). However, the locations of the boundaries  $r = 0$  and  $r = \pm 1$  are distinctive for these flows, because for computing the function  $r$  different resulting velocities of the vertical flows are used in (5).

The areas of the most R places are smaller in Fig.7 than in Fig.6. This fact takes place if both velocities  $v_{z,i}$  and  $v_{z,i+1}$  are positive. The area of the D place enlarges if  $v_{z,i} < 0$ ;  $v_{z,i+1} > 0$ .

For aquitards and for the  $m = 0$  areas of aquifers, the function  $r$  does not exist, because there  $v_{z,i} - v_{z,i+1} \sim 0$ .

## CONCLUSION

In the course of using the HM of Latvia LAMO4, the new method of finding borders of for the R, T, D areas has been developed. The method generalises the R, T, D concept by considering the four areas: R – recharge; +T positive transit; -T - negative transit; D – discharge. The areas are defined by the dimensionless function that applies the velocities of groundwater flows provided by the Groundwater Vistas system used by LAMO4. The new method can control the location of borders that separate the R, T, D areas. It is not necessary, as before, to use different control parameters for each aquifer of HM. The method is not sensitive to the change of the HM plane approximation step.

The new method will be applied for investigating the regional groundwater processes that are modelled by LAMO4.

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