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HYDROGEOLOGICAL MODEL OF WATER SUPPLY SYSTEM FOR THE PROSPECTIVE FACTORY OF COCA-COLA COMPANY, LATVIA

HIDROĢEOLOĢISKAIS MODELIS LATVIJĀ PLĀNOTĀS COCA-COLA RŪPNĪCAS ŪDENS APGĀDES SISTĒMAI

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***Keywords:** hydrogeological models, depression cone, chemical protection zone*

A hydrogeological model (HM) has been created for obtaining information confirming sustainability of the water supply system for the prospective factory of the Coca-Cola Company. HM covers the 9 km×10 km area located in the vicinity of the village Ropazi, Latvia. HM contains 11 layers, its plane approximation step is 20 metres. To estimate the water withdrawal impact on the groundwater body, the depression cones caused by the system were simulated for Quaternary and Devonian type aquifers. The location and area of the chemical protection zone were found. Through investigation has been performed, to find out that no worsening of water quality is expected under the influence of considerable and durable groundwater discharge (4000 m³/day during 25 years).

Introduction

The Coca-Cola Company has announced its intention to build factory in the vicinity of the Ropazi village that is located not far from the Riga city, Latvia (Fig. 1). The factory must have a sustainable water supply system. Its planned water consumption q=4000 m^3/day will be taken from the artesian groundwater aquifer.

A hydrogeological model (HM) has been created for obtaining data that are needed for receiving the permission to build the water supply system. HM must provide the following information:

- in Quaternary and artesian aquifers, depression cones must be computed that are caused by the system; consideration of these cones provides two answers: is the maximal lowering of the artesian head smaller that the allowed one; what is the influence of the new well field on the existing ones?;
- the location and area of the chemical protection zone must be found; within the zone, some economic activities are to be limited;
- expected worsening of water quality under the influence of a considerable and durable groundwater extraction.

The modeling system Groundwater Vistas (GV) [3] was used which included the following components: MODFLOW (hydrogeological model); MODPATH (finding of the chemical protection zone configuration); MT3D (investigation of mineralization changes). For graphical presentation of model results and for numerical data processing, the system SURFER [4] was used.

Fig. 1. Location of the model

HM is the steady state one. It simulates average annual groundwater conditions.

Creating of HM was based on the sources [1, 2], on the map [5] and on the materials [7] provided by the company “Water and Geology, Ltd.”.

Materials for preparing this paper were taken from the report [6].

The results provided by HM confirmed sustainability of the water supply system that should serve the prospective factory of the Coca-Cola Company.

The reported material may be of interest for modelers involved in problems of evaluation aftereffects caused by large well fields.

Basic mathematics of HM

To describe creating of HM, the mathematics of the 3D-steady state 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 s-tiered xy-layer system where s is the number of layers. 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 φ 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:

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

where A is the symmetric sparse 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; ψ - the boundary head vector: ψ_{rel}, ψ_{bot}, ψ_{sh} - subvectors on the HM top, bottom and shell, accordingly; G – the diagonal matrix (part of A) assembled by elements, linking the nodes where φ must be found with the ones were ψ is given; β - 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:

$$a_{xy}=k\times m,\ a_z=\frac{h^2\times k}{m}$$
$$m_i=z_{i-1}-z_i>0,\ i=1,2,...,s \tag{2}$$

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 with the hydrographical network included; k, m are, accordingly, elements of digital m, k-maps of the computed layer thickness and permeability.

The set of z-maps describes full geometry of HM. It is built incrementally: $z_0\rightarrow z_1,\ldots,z_s$ by keeping the thickness of the i-th layer $m_i>0$. If in some areas, $m_i=0$ then the i-th layer is discontinuous. To prevent the “division by zero”, in the a_z calculation of (2), $m_i=0$ must replaced by $\varepsilon>0$ (for HM, $\varepsilon=0.02$ metres). In GV, only the z-maps serve as the geometrical ones.

Obtaining the right distribution for the infiltration flow β_{inf} on the HM top is a burdensome task. For reported HM, this task was considerably eased by using the ψ_{rel}-map as the boundary condition for heads. Then the flow $\beta_{inf}=\beta_{aer}$ passes through the aeration zone:

$$\beta_{aer}=G_{aer}(\psi_{rel}-\varphi_Q) \tag{3}$$

where φ_Q is the computed head (subvector of φ) for the first aquifer Q; G_{aer} (diagonal submatrix of G) contains the vertical ties g_{aer} of the aeration zone connecting ψ_{rel} with φ_Q. The expression (3) gives the usual result of HM, when a ψ-condition is applied. As a rule, even the first run of HM provides feasible results for β_{inf}.

The elements g_{aer} of G_{aer} are computed, as follows:

$$g_{aer}=\frac{h^2\times k_{aer}}{m_{aer}},\ m_{aer}=\psi_{rel}-\varphi_Q\quad if\ \beta_{aer}>0$$
$$m_{aer}=1.0\quad if\ \beta_{aer}\le 0 \tag{4}$$

where k_{aer}, m_{aer} are, respectively, the permeability and thickness of the aeration zone. Initially, k_{aer}, m_{aer} are unknown. As the first try, the following values of these parameters may be applied: $m_{aer}=1.0$ metre; $k_{aer}=10^{-3}$ and 1.0 [m/day], accordingly, for the recharge areas ($\beta_{inf}>0$) and for the lines or areas of the hydrographical network. To avoid iterative changes of the HM geometry, $m_{aer}=1.0$ may be kept constant, until the calibrated state of HM is achieved. Only then, the real m_{aer} for the recharge areas ($\beta_{inf}>0$) must be introduced. The k_{aer}-distribution is the object of HM calibration.

For geological layers, their geometrical thickness is $m\ge m_{ef}$. The effective thickness m_{ef} accounts for the fact that, not always, the layer permeability is isotropic. Aquifers and aquitards may include admixtures, accordingly, of low and high permeability. Because the HM geometry is created on the thickness m-maps, the original k_{xy}, k_z-maps must be corrected, as follows:

$$(k_{xy})_c=k_{xy}\times C,\ (k_z)_c=k_z\times C^{-1},$$
$$c_i=\left(m_{ef}\times m^{-1}\right)_i\le 1.0 \tag{5}$$

where $(k_{xy})_c$, $(k_z)_c$ are the corrected permeability values; C is the diagonal correction matrix which is obtained by interpolating borehole data on the xy-grid planes of HM; c_i – the i-th initial element of C given by a borehole.

Hydrogeological model

The location of HM is given in Fig. 1. The HM area has the size 9000m×10000m. HM includes 11 layers (see Fig. 2 and 3). The approximation step h=20 metres. The HM grid includes six aquifers and five aquitards which control the vertical groundwater flows passing between adjacent aquifers. The ψ_{rel}-map is carried by the layer 1. Its small thickness m=0.02 metres does not disturb the HM geometry.

No.	Layer	Layer code	Thickness [m]	Permeability k [m/day]	Leakance of aquitards k_0/m_0 [1/day]
1	**Relief**	*rel*	0.02		
2	**Aeration zone**	*aer*	0.1 ÷ 10.0		$10^{-5}\times(2.6\div 14\times10^{4})$
3	**Quaternary aquifer**	*Q*	4.0 ÷ 37.5	12 ÷ 27	
4	**Morain (aquitard)**	*gQ*	1.0 ÷ 32.5		$10^{-3}\times(0.71\div2.3)$
5	**Amata aquifer**	*D3am*	0.02 ÷ 36.4	9	
6	**upper Gauja aquitard**	*D3gj2z*	0.02 ÷ 14.0		$10^{-3}\times(0.074\div21)$
7	**upper Gauja aquifer**	*D3gj2*	7.0 ÷ 42.7	10 ÷ 14	
8	**lower Gauja aquitard**	*D3gj1z*	1.5 ÷ 43.6		$10^{-4}\times(0.11\div3)$
9	**lower Gauja aquifer**	*D3gj1*	10.0 ÷ 64.0	5 ÷ 14	
10	**Burtnieki aquitard**	*D2brz*	3.0 ÷ 28.0		$10^{-5}\times(0.89\div 7.9)$
11	**Burtnieki aquifer**	*D2br*	50	8	

Fig. 2. Vertical schematization of the model and summary of parameters m, k, k_0/m_0

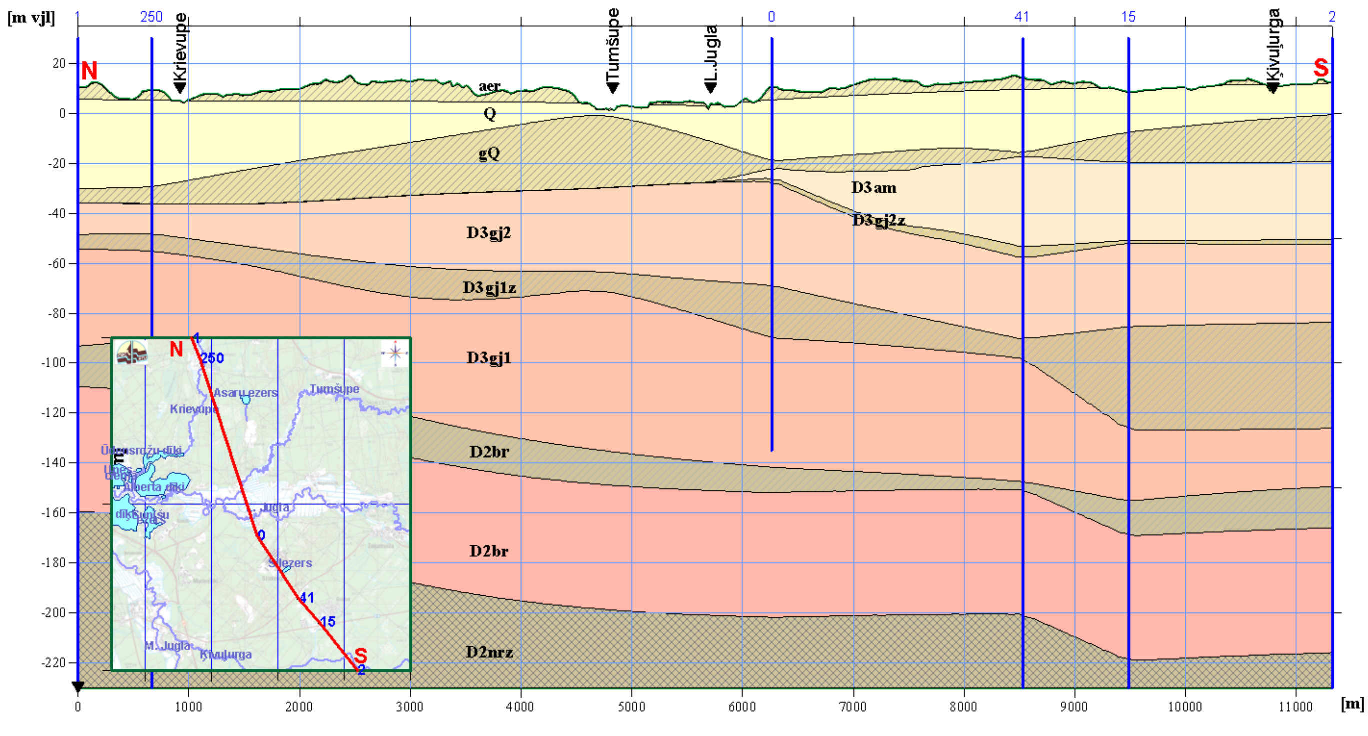


Fig. 3. Cross section NS of the model

The aeration zone (layer 2) is treated as a formal aquitard and serves as the tool for controlling the infiltration flow (eq. 3 and 4). The aquifer *D3am* and the aquitard *D3gj2z* (layers 5 and 6) are discontinuous. Four water production wells (q=4000m^3/day) will exploit the aquifer *D3gj2* (layer 7).

Conditionally, the thickness of the aquifer *D2br* (layer 11) is set m_{br}=50 metres. In HM, the bottom surface of this aquifer is impermeable. The computed φ_{br}-distribution is controlled by the boundary condition $(\psi_{sh})_{br}$, on the aquifer perimeter. Therefore, no fixed ψ_{bot}-map is applied.

HM accounts for the influence of two large well fields (in the aquifer *Q*, the southern part of the Zakumuiza siphon, q=7500 m^3/day; in the aquifer *D3gj2*, the well field of Zakumuiza, q=20500 m^3/day) which supply the Riga city with drinking water.

Because these well fields are located in the northern part of HM, there the shell for the aquifers *Q*, *D3am*, *D3gj2*, *D3gj1* is set impermeable. For these four aquifers, on the other three planes of the shell, the ψ_{sh}-conditions are fixed. The z-maps of geological layers were produced by SURFER by applying data provided by 46 boreholes [6].

The k-maps were created by SURFER by using information, given in the reference [1]. For the prospective water supply system area, new data were provided by the experimental borehole group No.0 [6, 7]. For the aquifer *Q*, the anisotropy k_z/k_{xy}=0.1 was used.

To account for the fact that $m \geq m_{ef}$, the correction (5) was applied for the k-maps. The matrix *C* was created by SURFER.

In Fig. 4, calibration targets (points) are shown. Six of them are monitoring wells; the other four represents the HM area corners. The head values for these points were taken from the map [5].

The 3000m×3000m area (Fig. 4) was used for groundwater flow calculations.

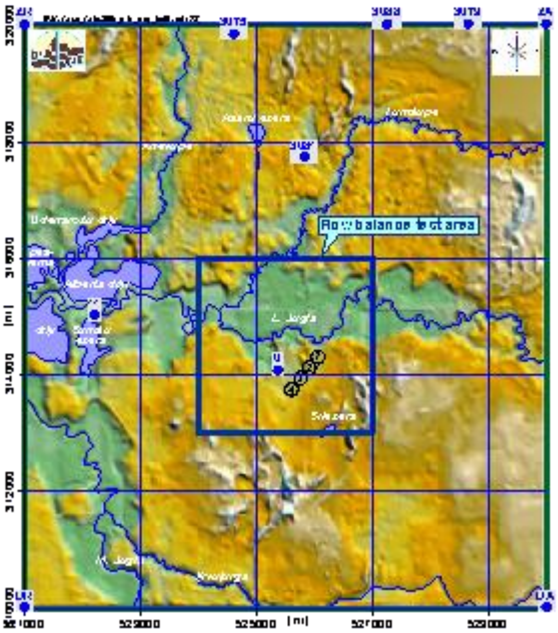


Fig. 4. Calibration targets and the model flow balance area

For the aquifers *Q*, *D3gj2*, *D3gj1*, the maps of undisturbed heads (q=4000 m^3/day not accounted for) are shown in Fig. 5. The φ_{br}-map for the aquifer *D2br* is rather similar to the one of the aquifer *D3gj1*. The φ_{br}-distribution heads are about 3.5 metres higher than the ones of the φ_{D3gj1}-map. The ψ_{sh}-conditions were mostly obtained from the model [2].

The head distribution of the aquifer *Q* is mainly determined by the ψ_{rel}-map, especially, by the L.Jugla river. This river also has a considerable impact on the head distribution of the aquifer *D3gj2*.

As it follows from Fig. 5, in the area of the new well field (wells 1, 2, 3, 4), the ascending vertical groundwater flow exists. Due to this phenomenon, mineralization of the aquifer *D3gj2* may increase, because the natural mineralization in the aquifers *D3gj1* and *D2br* are higher. By using HM, this problem has been thoroughly investigated.

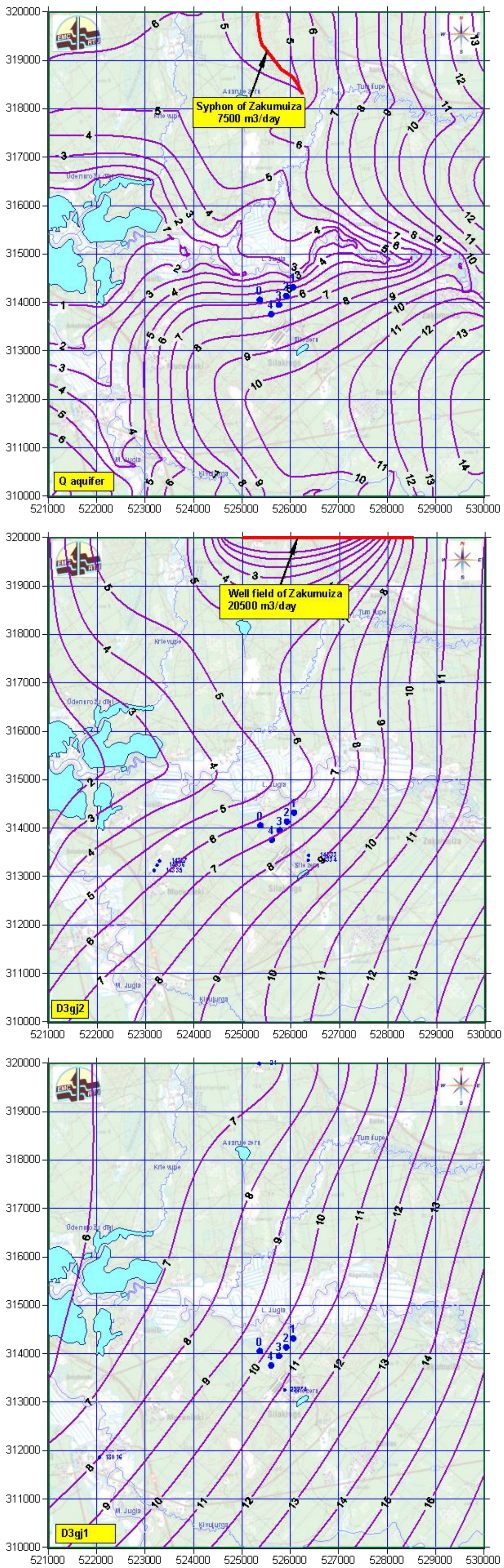


Fig. 5. Maps of undisturbed heads [m asl] for aquifers *Q*, *D3gj2*, *D3gj1*

Evaluation of the new water supply system

The new water supply system contains four abstraction wells. Their total production rate q=4000 m^3/day is provided by the aquifer *D3gj2*. The dynamic head distribution of the aquifer *D3gj2* is given by Fig. 6.

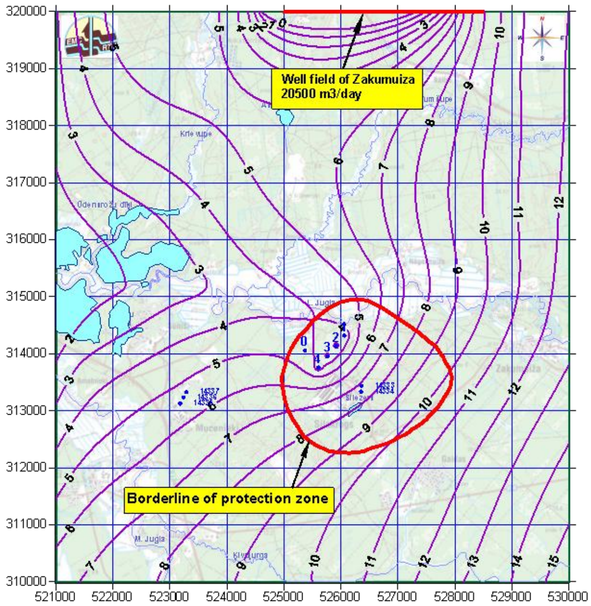


Fig. 6. Head distribution [m asl] of the aquifer *D3gj2* if the water production rate is 4000 m^3/day; the borderline of the chemical protection zone is shown

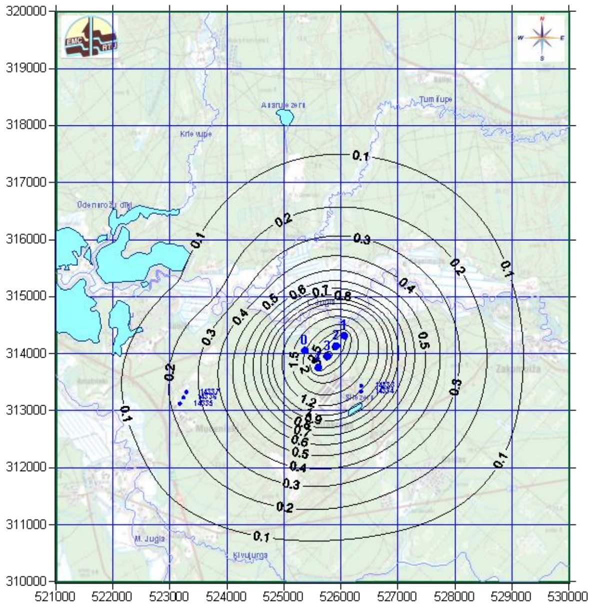


Fig. 7. Depression cone in the aquifer *D3gj2*

The depression cone that is caused by this groundwater withdrawal is shown in Fig. 7. The modeled drawdown maximum S_r=4.9 metres there corresponds with the equivalent abstraction well radius 0.2h=4 metres that is much larger than the real well screen radius r_w. For this reason, the real expected drawdown S must be computed, as follows:

$$S = S_R + S_A,\ S_A = \frac{q}{2\pi km}\times\left(\ln\frac{0.2h}{r_w}+\xi\right) \quad (6)$$

where S_A is the analytical correction; S_R=4.9 m is given by HM; q=1000 m^3/day is the abstraction rate of a single well; km=300m^2/day – the mean transmissivity; r_w=0.105 m; h=20 m; ξ=5.0 is the well hydraulic resistance. Information about the values of r_w and ξ is given by [7].

The formula (6) gives S=9.07 m = (4.9+4.17) m. For the area of the water supply plant, the maximally allowed drawdown is 39.5 metres [6, 7]. The maximal drawdown S that is caused by the new well field, is much smaller than the allowed one (39.5>>9.07). Therefore, the discharge q=4000 m^3/day will not cause inadmissible changes of the groundwater system.

As it follows from considering of the depression cone in the aquifer *D3gj2* (Fig. 7), the new water supply plant will not distort significantly regimes of the two small neighboring well fields. Their total withdrawal rate q=98.8 m^3/day It is shown in the report [6] that the following maximal drawdowns [metres] are expected (at the centre of the new well field) in the aquifers *Q*, *D3gj1*, *D2br*, accordingly: 0.5; 0.25; 0.04. Therefore, the proposed water supply system will not cause significant distortions in regimes of any existing well field located within the HM body.

Configuration of the chemical protection zone is shown in Fig. 6. It was obtained by using the MODPATH system where water particle tracers were run in the reverse regime for the 25 year exploitation time of the system. The zone area is 577 ha. The value of porosity n=0.1 was applied, to create the zone

Migration of natural contaminants

It has been found out that no anthropogenic contaminant sources are located within the area of the chemical protection zone. The four experimental boreholes (group No.0) provided data about the concentrations of SO_4 and Cl in the aquifers *Q*, *D3gj2top*, *D3gj2bot*, *D3gj1*. Mineralization in the aquifer *D3gj2* was checked in its top and bottom parts. The new well field will exploit the bottom part *D3gj2bot*. The mineralization data are given by Table 1. It follows from the table that aquifers *Q* and *D3gj2top* practically are clean regarding the SO_4 and Cl ions. The aquifer D3gj1 has the highest concentrations of SO_4 and Cl. The mineralization of the bottom part *D3gj2bot* meets standards for drinking water. However, it is not clear how the groundwater withdrawal will affect mineralization there during 25 years of the planned exploitation time of the system.

It was found out that after 23 days of pumping from the aquifer D3gj2bot (q=475m^3/day), the concentration [mg/l] for the SO_4 and Cl ions decreased: 105.0→26.5; 153.0→42.1, respectively [7].

To explain reasons for the observed decrease of mineralization, the groundwater flow balance was obtained for the 3000m×3000m test area. Two regimes were checked: undisturbed HM, disturbed HM (q=4000m^3/day).

Table 1

Mineralization of groundwater [mg/l] at the area of experimental boreholes

Layer	SO_4 [mg/l]	Cl [mg/l]
Q	8.2	1.4
D3gj2top	4.9	2.4
D3gj2bot	105.0	153.0
D3gj1	217.0	368.0

The result of this numerical experiment is given by Table 2. The 3rd row of Table 2 (difference between the two regimes) shows that the discharge q=4000m^3/day is supplied from the following sources: 55.5% from the aquifers *Q*, *D3am* (fresh water); 38% from the aquifer *D3gj2* itself (mildly mineralized water); 6.5% from the aquifer *D3gj1* (mineralized water). This result not only explains why the observed mineralization in the aquifer *D3gj2* has decreased, but also confirms that no worsening of the groundwater quality is expected under the groundwater withdrawal influence.

An extra numerical test was performed regarding the possible worsening of the groundwater quality. Migration of natural contaminants from the aquifer *D3gj1* was simulated by using the MT3D system. Consideration of the above simulation results obtained by the MT3D system provides an extra confirmation that no worsening of the groundwater quality will happen during 25 years of the planned exploitation time of the new water supply system. In other layers of HM, the initial concentration was zero.

The ascending contaminant migration *D3gj1→D3gj2z→D3gj2* was simulated for the undisturbed and disturbed regimes of HM. To obtain the graphs of concentration changes during 25 years, the virtual monitoring wells were set in the layers *D3gj2*, *D3gj1z*, *D3gj1*. Their coordinates coincided with the ones of the abstraction well No.3 (Fig. 8). The computed concentration distribution, in the aquifer *D3gj2* after 25 years, is shown in Fig. 8 (disturbed HM).

It follows from Fig. 8 that the concentration maximum is located near to the L.Jugla river, because there the ascending vertical groundwater flow *D3gj1→D3gj2* is stronger (60 mm/year) than in the vicinity of the abstraction well No.3 (40 mm/year) [6].

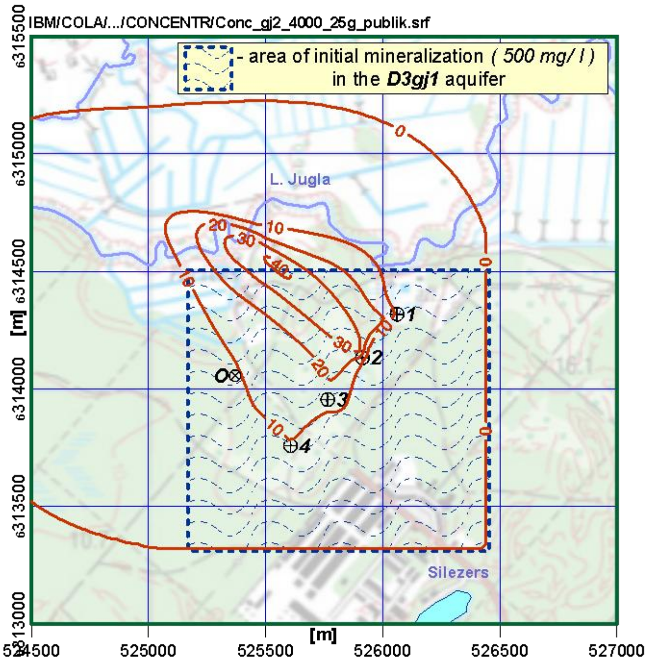
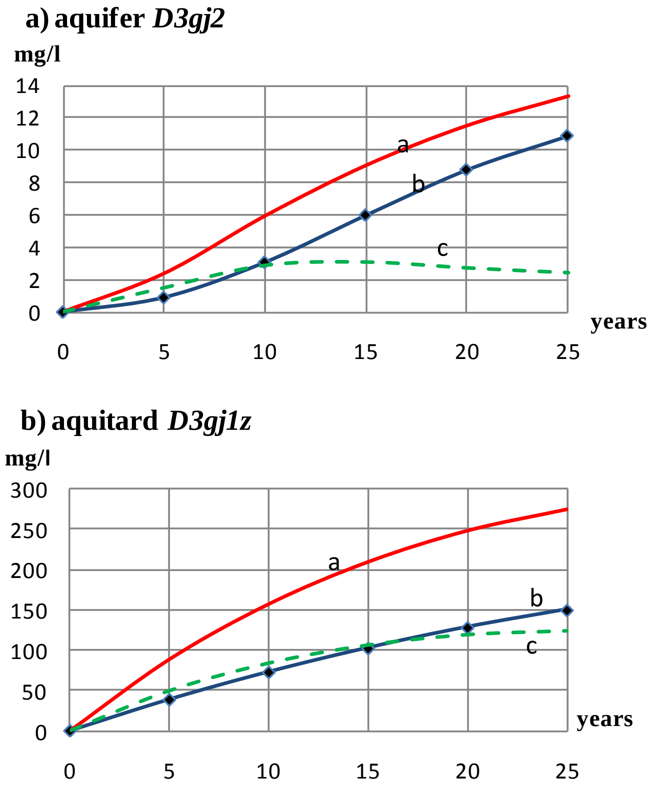


Fig. 8. Area of water abstraction wells, aquifer *D3gj2* mineralization [mg/l] after 25 years

More general information regarding the contaminant migration is presented by graphs of Fig. 9. Three types of graphs are considered: the changes of mineralization for undisturbed and disturbed HM, accordingly; the difference between the above two ones.



b/a- un/disturbed condition; c- difference graph b-a

Fig. 9. Changes of mineralization [mg/l] versus time

It follows from the difference graph of Fig. 9a that due to the inflow of fresh water from the aquifers *Q* and *D3am*, the mineralization increase keeps practically constant and small (2 mg/l), after 25 years. In the aquitard *D3gj1z* (Fig. 9b), the difference graph reaches 125 mg/l after 25 years.

Consideration of the above simulation results obtained by the MT3D system provides an extra confirmation that no worsening of the groundwater quality will happen during 25 years of the planned exploitation time of the new water supply system.

Table 2

Groundwater flows for the D3gj2 aquifer test area (Fig. 4)

	Regime	Lateral xy – flows [m^3/day]					Vertical flows [m^3/day]		Well rates [m^3/day]
		q_W	q_N	q_E	q_S	q_{xy}	q_{gj2z}	q_{gj1z}	q_V
1.	Undisturbed	-996.3	532.4	1915.2	1136.5	2587.8	-3950.0	1461.0	-98.8
2.	Disturbed	-706.3	718.6	2405.6	1685.5	4103.4	-1730.0	1725.4	-4098.8
3.	Difference 2.-1.	290.0	186.2	490.4	549.0	1515.6	2220.2	264.4	-4000

q_{xy} - flow through perimeter ($q_W + q_N + q_E + q_S$)= q_{xy};
q_{gj1z} - flow through the *D3gj1z* aquitard;
q_{gj2z} - flow through the *D3gj2z* aquitard;
q_V - well rate;

Conclusions

The 3D hydrogeological model has been created for obtaining information confirming sustainability of the water supply system for the prospective factory of the Coca-Cola Company. By applying the model, the following results have been obtained:

- the system will not cause any significant changes in the distributions of the groundwater heads;
- the configuration of the chemical protection zone has been obtained;
- no worsening of the groundwater quality is expected during 25 years of the planned exploitation time of the system.

Therefore, the above results provide information needed for obtaining the permission to construct the water supply system.

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   - information about groundwater abstraction rates, 2008;
   - data about experimental and abstraction wells of the new well field;
   - information of abstraction well screens;
   - data about mineralization in boreholes.

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A.Spalviņš , J.Šlangens, I.Lāce, K.Krauklis. Hidroģeoloģiskais modelis Latvijā plānotās Coca-Cola rūpnīcas ūdens apgādes sistēmai
Izveidots hidroģeoloģiskais modelis (HM) Latvijā plānotajai Coca-Cola kompānijas rūpnīcas ūdens apgādes sistēmas ilgtspējīgas darbības novērtēšanai. HM aptver 9km×10km laukumu, kurš atrodas Ropažu ciemata apkārtnē. HM sastāv no 11 slāņiem, plaknes aproksimācijas solis ir 20 metri. Lai novērtētu ūdens atsūknēšanas iespaidu uz pazemes ūdens sistēmu, tika aprēķinātas depresijas

piltuves Kvartāra un Devona tipa ūdens horizontiem. Atrasts ķīmiskās aizsargjoslas novietojums. Rūpīgi izpētīts, ka nav sagaidāma ūdens kvalitātes pasliktināšanās, kuru varētu izraisīt ilgstošs un nozīmīgs pazemes ūdens patēriņš (4000 m^3/dien 25 gadu laikā).

А.Спалвиньш, Я.Шлангенс, И.Лаце, К.Крауклис. Гидрогеологическая модель для системы водоснабжения планируемого завода компании Coca-Cola, Латвия
Построена гидрогеологическая модель (ГМ) для получения информации необходимой для проектирования системы водоснабжения для завода компании Coca-Cola. ГМ покрывает площадь размером 9км×10км, в окрестностях посёлка Ропажи, в Латвии. ГМ содержит 11 слоёв, шаг плоскостной аппроксимации равен 20 метрам. Для оценки влияния отбора воды на гидрогеологический режим, были смоделированы конусы депрессии в водоносных горизонтах Четвертичных и Девонных типов. Определена конфигурация и площадь химической защитной зоны. Было проведено тщательное исследование, которое показало, что не ожидается понижение качества воды, которую может вызвать существенный и длительный отбор воды (4000 $м^3$/день в течение 25 лет).