Implementations of Riga city water supply system founded on groundwater sources

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Abstract. Drinking water for Riga city is provided by the groundwater well field complex “Baltezers, Zakumuiza, Rembergi” and by the Daugava river as a surface water source. Presently (2016), the both sources jointly supply 122 thous. metre$^3$day$^{-1}$ of drinking water. It seems reasonable to use in future only groundwater, because river water is of low quality and its treatment is expensive. The research on this possibility was done by scientists of Riga Technical university as the task drawn up by the company ”Aqua-Brambis”. It was required to evaluate several scenario of the groundwater supply for Riga city. By means of hydrogeological modelling, it was found out that groundwater well fields could provide 120-122 thous. metre$^3$day$^{-1}$ of drinking water for the Riga city and it is possible further not to use water of the Daugava river. However, in order to provide more extensive use of groundwater sources, existing water distribution network shall be adapted to the change of the water sources and supply directions within the network. Safety of water supply shall be ensured. The publication may be of interest for specialists dealing with problems of water supply for large towns.

1. Introduction
The first groundwater well field for the centralized water supply for Riga city was made at the Baltezers region in 1904. This syphon type system “Baltezers” is still in operation. The well field covered demand of drinking water up to the middle of 1930-ties. In 1935, the additional groundwater well field Zakumuiza was established.

After World War II, new groundwater well fields for the centralized system were established: Baltezers 1, in 1959; Rembergi, in 1962; Gauja experimental, in 1966; Gauja-1, in 1968; Katlakalns, in 1968; Baltezers 2, in 1974.

Since 1967, surface water from the Jugla lake was used. Its quality has never matched the drinking water standards. However, until 1998, this source of water was used.

In 1978, the surface water intake “Daugava” was constructed. It uses water of the Daugava river from the reservoir of the Riga Hydroelectric Power Plant. To meet the drinking water standards, raw water or the river is treated using treatment with ozone, coagulation and filtration.

The summary on the centralized water supply of Riga city [1, 2, 3] is presented in table 1. The yields of well fields in 1991 and 2015 are shown. In 1991, the yield 420.5 thous.metre$^3$day$^{-1}$ was reached. It included the yields of groundwater and surface water sources 239.5 thous.metre$^3$day$^{-1}$ and 190.0 thous.metre$^3$day$^{-1}$, accordingly. The well fields Baltezers and Baltezers 2 applied the artificial recharge of the Quaternary aquifer Q by using water from the lake M. Baltezers.
Table 1. Summary on well fields for centralized water supply of Riga city [1, 2, 3].

| Name of well field | Year of opening | Source of water | Year of opening | Water take out mode | Water treatment required | Yield (thous. metre$^3$ day$^{-1}$) | Recharge$^a$ (thous. metre$^3$ day$^{-1}$) |
|--------------------|-----------------|----------------|----------------|--------------------|-------------------------|----------------------------------|-----------------------------------|
| Baltezers          | 1904            | Q              | 1991           | syphon             | yes                     | 58.1                             | 19.0                              | 72.0                              |
| Baltezers 1        | 1959            | Q              | 2015           | syphon             | yes                     | 27.5                             | 9.6                               | -                                 |
| Baltezers 2        | 1974            | Q              | 1991           | syphon             | yes                     | 28.5                             | -                                 | 24.2                              |
| Rembergi           | 1962            | Q              | 1991           | syphon             | no                      | 19.2                             | 12.0                              | -                                 |
| Zakumuiza          | 1935            | Q              | 1991           | syphon             | no                      | 27.8                             | 10.0                              | -                                 |
| Zakumuiza D        | 2006            | D3gj           | 1991           | pumps              | no                      | -                                | 10.5                              | -                                 |
| Gauja              | 1966            | Q              | 1991           | pumps              | yes                     | 68.4$^b$                         | -                                 | -                                 |
| Katlakalns         | 1968            | D3gj           | 1991           | pumps              | yes                     | 10.0                             | -                                 | -                                 |
| Groundwater total  |                 |                |                |                    |                         | 239.5                            | 61.1                              | 96.2                              |
| Sources of surface water |            |                |                |                    |                         | 420.5                            | 124.7                             | -                                 |
| Daugava            | 1978            | river          | 1991           | pumps              | yes                     | 150.0                            | 63.6                              | -                                 |
| Jugla              | 1967            | lake           | 1991           | pumps              | yes                     | 40.0                             | -                                 | -                                 |

$^a$ No artificial groundwater recharge in 2015

$^b$ Total yield of Gauja 1 and Gauja experimental

$^c$ Q and D3gj – codes of Quaternary and Devonian aquifers

The yield 124.7 thous. metre$^3$ day$^{-1}$, in 2015, represents the current situation of the water supply: 61.1 thous. metre$^3$ day$^{-1}$ and 63.6 thous. metre$^3$ day$^{-1}$ are supplied, respectively, from groundwater and surface water sources. No artificial groundwater recharge is used. For this reason, the current productivity of Baltezers is only 19.0 thous. metre$^3$ day$^{-1}$, but Baltezers 2 is not used. The well fields Gauja-1, Gauja experimental and Katlakalns were closed in 2000 and in 2004, accordingly. In 2006, the new well field Zakumuiza D was established. It can take 30.0 thous. metre$^3$ day$^{-1}$ of artesian water from the Devonian aquifer D3gj$^2$. However, in 2015, only 10.5 thous. metre$^3$ day$^{-1}$ of water (35% of capacity) was supplied.

Presently, the complex of Baltezers, Rembergi, Zakumuiza well fields is the only provider of drinking water from groundwater sources. Its available production is 112.7 thous. metre$^3$ day$^{-1}$. It is founded on the estimate (19.0+27.5+19.2+17.0+30.0) thous. metre$^3$ day$^{-1}$ where the yields of 1991 are used for Baltezers 1 and Rembergi, but the yield of Zakumuiza is reduced from 27.8 to 17.0, due to the influence of Zakumuiza D [1].

From information of table 1, the following conclusions can be drawn: since 1991, the drinking water consumption of Riga city has decreased 3.37 times; in 2015, the available capacity of groundwater and surface water sources was exploited only 54% and 42%, accordingly; the groundwater sources in 1991 and 2015 had provided, respectively, 60% and 49% of the total yield.

In 1995, it was expected that, in 2010, the water demand should be 340 thous. metre$^3$ day$^{-1}$ [4]. In order to accomplish this goal, the Daugava river water treatment plant and the complex of Baltezers, Rembergi, Zakumuiza well fields have been considerably renovated [2].

Since Riga city is facing decrease of population, it is expected that, in 2030, the water demand of Riga city will be only 122 thous. metre$^3$ day$^{-1}$, providing supply for about 700 000 inhabitants. This amount may be supplied from groundwater sources. The possibility has been investigated by scientists of Riga Technical University as the task drawn up by the company “Aqua-Brabmis” [5].

Five scenarios of water supply for Riga city were investigated. The summary on the scenarios is presented in table 2.
Table 2. Summary on yield of well fields (thous. metre$^3$/day$^{-1}$) for scenarios of water supply [5].

| Name of well field | Scenario number |
|--------------------|-----------------|
|                    | 1. | 2. | 3. | 4. | 5. |
| Baltezers          | 19.0 | 19.0 | 19.0 | 19.0 | 28.0* |
| Baltezers 1        | 9.6 | 9.6 | 9.6 | 9.6 | 30.0* |
| Baltezers 1D       | - | - | - | 15.0* | - |
| Baltezers 2        | - | - | - | - | - |
| Rembergi           | 12.0 | 17.0 | 17.0 | 17.0 | 17.0* |
| Rembergi D         | - | - | - | 15.0* | - |
| Zakumuiza          | 10.0 | 17.0 | 17.0 | 17.0 | 17.0* |
| Zakumuiza D        | 10.5* | 28.5* | 30.0* | 30.0* | 30.0* |
| Daugava D          | - | - | - | 30.0* | - |
| Daugava            | 63.6 | 31.8 | - | - | - |
| Total              | 124.7 | 122.0 | 122.6 | 122.6 | 122.0 |

* Submersible pumps used

2. Scenarios of water supply

The scenario 1 is the current water supply and its features were considered above.

For the scenario 2, the yield of the intake Daugava is reduced twice in comparison with its current production (63.6→31.8). The yield 31.8 thous. metre$^3$/day$^{-1}$ is the minimal amount of water that can be treated, not harming the water treatment process. To support the yield 122.0 thous. metre$^3$/day$^{-1}$, productivity of the wells fields Rembergi, Zakumuiza and Zakumuiza D have to be increased.

The scenarios 3, 4, 5 do not use surface water. For the scenario 3, the intake Daugava is replaced by the new well field Daugava D that uses artesian water of the Devonian aquifer D3gj. Such possibility has been considered in 1996, when alternative groundwater sources were sought [6].

To supply extra 30.0 thous. metre$^3$/day$^{-1}$, the scenario 4 uses artesian water of the Devonian aquifer D3gj1. The wells of Baltezers D and Rembergi D are located along the syphon lines of Baltezers and Rembergi, correspondingly (see table 3).

Table 3. Parameters of syphons and submersible pump systems.

| Name of well field | Length (metre) | Wells of syphons | Wells with submersible pumps |
|--------------------|----------------|------------------|-----------------------------|
|                    |                | Number | Distance (metre) | Number | Distance (metre) |
| Baltezers          | 5900           | 121    | 48.7            | 20     | 295.0            |
| Baltezers 1        | 2900           | 72     | 40.3            | 20     | 145.0            |
| Baltezers 1D       | 2900           | -      | -               | 20     | 145.0            |
| Baltezers 2        | 1200           | 20     | 60              | -      | -                |
| Rembergi           | 4600           | 41     | 112.2           | 12     | 383.3            |
| Rembergi D         | 4600           | -      | -               | 12     | 383.3            |
| Zakumuiza          | 3800           | 90     | 42.2            | 12     | 316.7            |
| Zakumuiza D        | 3000           | -      | -               | 9      | 333.3            |
| Daugava D          | 4000           | -      | -               | 22     | 181.8            |

For the scenario 5, all syphons are replaced with submersible pump systems. In table 3, results of the replacement are provided. If the syphons are replaced then the number of wells considerably decreases and the yields of well fields can be increased.
3. Modelling of groundwater well fields

To evaluate the water supply scenarios, the hydrogeological model (HM) of the complex “Baltezers, Rembergi, Zakumuiza” was used. In 2005, HM was established and, in 2016, it was renovated [7]. Presently, HM is run by the licensed modelling system Groundwater Vistas 6 (GV) [8].

The HM area is 11000 metres × 10450 metres. HM accounts for well fields, rivers and lakes (see figure 1). The vertical schematisation and parameters of HM are presented in table 4.

### Table 4. Vertical schematisation and parameters of hydrogeological model [7].

| No of HM layer | Name of layer          | Code of layer | $m_{\text{mean}}$ (metre) | $k_{\text{mean}}$ (metre day$^{-1}$) | Notes                                             |
|----------------|------------------------|---------------|---------------------------|--------------------------------------|--------------------------------------------------|
| 1              | Relief                 | relh          | 0.02                      | 10.0                                 | Boundary conditions                              |
| 2              | Aeration zone          | aer           | 3.0                       | 3.4 $10^{-4}$                        |                                                  |
| 3              | Quaternary sand Q1     | Q1            | 14.2                      | 32.2                                 | Connected with lakes and rivers                  |
| 4              | Quaternary sand Q2     | Q2            | 14.2                      | 32.2                                 | Connected with wells                              |
| 5              | Quaternary moraine     | gQz           | 10.8                      | 2 $10^{-4}$                          |                                                  |
| 6              | Upper Gauja D3gj2      | D3gj2         | 22.0                      | 10.0                                 | Connected with wells                              |
| 7              | Lower Gauja D3gj1z     | D3gj1z        | 9.1                       | 2 $10^{-4}$                          |                                                  |
| 8              | Lower Gauja D3gj1      | D3gj1         | 28.6                      | 10.0                                 | Connected with wells                              |

$m_{\text{mean}}$ and $k_{\text{mean}}$ – the mean thickness and permeability of layers

HM includes eight layers and accounts for the Quaternary and Devonian aquifers Q and D3gj2, D3gj1, accordingly. The aquifer Q is split into two equal parts Q1 and Q2. The part Q1 is connected with lakes, rivers and with infiltration basins for artificial groundwater recharge. Exploitation wells are connected with the aquifer Q2 (syphons) and with the aquifers D3gj2 and D3gj1 (submersible pumps).

In figures 1(a) and 1(b), the undisturbed groundwater head $\varphi_{\text{und}}$ (m asl-metres above sea level) distributions are shown, accordingly, for the aquifers Q2 and D3gj2. The undisturbed condition corresponds to the case when no abstraction of groundwater by exploitation wells takes place.

![Figure 1](image1.png) (a) ![Figure 1](image2.png) (b)

The boundary conditions as the fixed heads are set on the HM top (Relief) and on the vertical outer borders (shell) of HM. The bottom surface of the aquifer D3gj1 is impermeable. Rivers and lakes are simulated by the GV options “River” and “GHB” (General Head Boundary), correspondingly. The
aeration zone aer acts a formal aquitard which controls the infiltration flow of the aquifer Q1. The plane approximation step of HM is 55 metres.

Groundwater abstraction results in decreased head distribution $\phi_{din}$. The difference $\phi_{乡} - \phi_{din} = S$ (metre) is the depression cone of the well field. The maximal value of $S$ (depth of the cone) for syphons is 6-7 metre. For the submersible pumps, the depth of a cone is limited only by drying of the aquifer. For all investigated scenarios, the well fields included in HM were acting simultaneously and the computed depths of depression cones account for interaction of the well fields (see table 5).

In figures 2(a) and 2(b), the depression cones are shown, accordingly, for the aquifers Q2 and D3gj2 of the scenario 5. The scenario applies maximal groundwater intakes for the aquifers Q2 and D3gj2.

![Figure 2. Depression cones (metre) for scenario 5; (a) aquifer Q2; (b) aquifer D3gj2.](image)

It follows from table 5 that the capacity of syphons is unused for all scenarios, because the depths of their depression cones do not exceed 4.3 metre.

| Name of well field | Depth of cone (metre) for scenarios Nos 1-5 |
|--------------------|--------------------------------------------|
|                    | 1   | 2   | 3   | 4   | 5   |
| Baltezers          | 2.2 | 2.4 | 2.4 | 2.4 | 3.9*|
| Baltezers 1        | 2.9 | 3.2 | 3.4 | 3.4 | 7.8*|
| Baltezers 1D       | -   | -   | -   | 22.5*| -   |
| Rembergi           | 3.0 | 4.0 | 4.3 | 4.3 | 5.3*|
| Rembergi D         | -   | -   | -   | 22.5*| -   |
| Zakumuiza          | 2.5 | 4.2 | 4.3 | 4.3 | 4.8*|
| Zakumuiza D        | 11.2*| 30.6*| 32.8*| 32.8*| 32.8*|
| Daugava D          | -   | -   | 35.4*| -   | -   |

* submersible pumps used

For the submersible pumps case, the computed depths of depression cones are smaller than the real ones. The difference $\Delta S$ can be computed by using the formula:
\[ \Delta S = \frac{q}{2\pi T} \left( \ln(0.2hr^{-1}) + \xi \right) \]  

where \( q \) is the productiveness of a well (metre\(^3\)day\(^{-1}\)); \( T \) is the transmissivity (metre\(^2\)day\(^{-1}\)) of the aquifer; \( h \) is the plane step of HM; \( r \) is the radius of the well screen; \( \xi \) is the additional nondimensional parameter that accounts for imperfection of the well.

The relationship \( 0.2h \) shows that \( \Delta S \) exists within a circle of the radius \( 0.2h \); the circle centre is the well [9].

If \( h = 55 \) metre, \( r = 0.2 \) metre; \( \xi = 4.0 \); \( T_Q = 914 \) metre\(^2\)day\(^{-1}\); \( T_{D3gj2} = 220 \) metre\(^2\)day\(^{-1}\), the formula (1) gives \( \Delta S_Q \) and \( \Delta S_{D3gj2} \) for the aquifers Q and D3gj2 (see table 6).

It follows from table 6 that appliance of submersible pumps for the aquifer Q causes small \( \Delta S \).

**Table 6. Additional drawdown \( \Delta S \) (metre) for wells.**

| Type of well             | \( q \) (metre\(^3\)day\(^{-1}\)) | \( \Delta S_Q \) (metre) | \( \Delta S_{D3gj2} \) (metre) |
|-------------------------|---------------------------------|---------------------|-------------------------|
| Syphon                  | 150                             | 0.2                 | -                       |
| With submersible pump   | 1400                            | 1.9                 | 8.1                     |

### 4. Groundwater flow balance

By using the GV option “Mass balance”, the groundwater flow balances for water supply scenarios were obtained (see table 7). The flow balance shows how the groundwater flow distributes within each aquifer of HM: the flows passing through the top and bottom surfaces of an aquifer result in the infiltration which is spent by rivers, lakes, border and exploitation wells. For the undisturbed condition (no water abstraction), the infiltration 55.34 thous.metre\(^3\)day\(^{-1}\) is spent by rivers, lakes and border, accordingly, as the flows -33.89; -22.04 and 0.59 (thous.metre\(^3\)day\(^{-1}\)).

**Table 7. Groundwater flow balance (thous.metre\(^3\)day\(^{-1}\)) [5]**

| Aquifer | Top 1 | Bottom 3 | Infiltration 4=2+3 | Rivers 5 | Lakes 6 | Borders 7 | Wells 8 |
|---------|-------|----------|-------------------|---------|---------|-----------|---------|
|         |       |          | Unaffected condition |         |         |           |         |
| Q1      | 55.34 | 0.78     | 56.12             | -33.89  | -22.04  | -0.19     | 0       |
| Q2      | -0.78 | 0.28     | -0.50             | 0       | 0       | 0.50      | 0       |
| D3gj2   | -0.28 | -1.16    | -1.44             | 0       | 0       | 1.44      | 0       |
| D3gj1   | 1.16  | 0        | 1.16              | 0       | 0       | -1.16     | 0       |
| **Total** | 55.34 | -33.89   | -22.04            | 0       | 0       | 0.59      | 0       |
| Q1      | 68.17 | -45.70   | 22.47             | -22.43  | -4.99   | 4.95      | 0       |
| Q2      | 45.70 | -0.77    | 44.93             | 0       | 0       | 5.67      | -50.60  |
| D3gj2   | 0.77  | 1.36     | 2.13              | 0       | 0       | 8.57      | -11.70  |
| D3gj1   | -1.36 | 0        | -1.36             | 0       | 0       | 1.36      | 0       |
| **Total** | 68.17 | -22.43   | -4.99             | 20.55   | -62.30  | 0         |         |
| Q1      | 80.72 | -85.93   | -5.21             | -10.98  | 7.51    | 8.68      | 0       |
| Q2      | 85.93 | -3.45    | 82.48             | 0       | 0       | 9.52      | -92.00  |
| D3gj2   | 3.45  | 5.10     | 8.55              | 0       | 0       | 21.45     | -30.00  |
| D3gj1   | -5.10 | 0        | -5.10             | 0       | 0       | 5.10      | 0       |
| **Total** | 80.72 | -10.98   | 7.51              | 44.75   | -122.00 | 0         |         |

In the case of the current water supply (scenario 1), the infiltration flow increases (55.34 →68.17), in comparison with the undisturbed condition. The discharge flow of wells (-62.30) is mostly supported by the increased inflow through the border (0.59→20.55) and by the decrease of flows of rivers and lakes (-33.89→22.43; -22.04→-4.99).
For the scenario 5, the changes of the groundwater flows are considerably larger than for the scenario 1: the discharge 30.0 thous.m³ day⁻¹ of Zakumuiza D is supported mainly by the inflow 21.45 thous.m³ day⁻¹ through the border of the aquifer D3gj2. The discharge 92.0 thous.m³ day⁻¹ is based on the infiltration flow 82.48 thous.m³ day⁻¹ and on the inflow 9.52 thous.m³ day⁻¹ passing through the border of the aquifer Q2.

The groundwater flow balances provide valuable knowledge about the complex process of extracting water for exploitation wells.

5. Water distribution network and its safety
The Daugava river splits Riga city into two parts: the western and eastern Riga (RW and RE). Presently, RE contributes about 88 thous.m³ day⁻¹. In table 8, the summary is presented on yields of water sources of RW and RE for the scenarios of water supply. The Daugava river and the new well field Daugava D provide water for RW (scenarios 1, 2, 3). This feature eases the problem of water transfer between RW and RE, since the 1978 water distribution network has been developed to provide biggest share of supply from WTP Daugava. For the scenarios 4 and 5, water sources are located only at RE and about 34 thous.m³ day⁻¹ should be transferred to RW. This circumstance causes the problems of water distribution reliability and safety, as well as efficiency of supply. Indicative hydraulic estimates showed that change of water supply scenario to use water source only from RE requires relatively big investments to optimise volumes and distribution of water reservoirs within the network as well as strengthen water supply mains which provide water from RE side to RW side of the city [10]. It also requires more detailed analysis of required water pressure in the network, to ensure economically feasible and cost effective solution of the water supply for the city in the near future.

Impact of daily consumption changes can be smoothed by help of underground water reservoirs. For the cases of long time accidents or repair works, the additional water sources must be applied: extra wells with submersible pumps at the “Baltezers, Rembergi, Zakumuiza” area, Daugava D (if established), artificial groundwater recharge for Baltezers 2 and the western part of Baltezers, water from the Daugava river.

6. Conclusions
It follows from investigation of possible scenarios of water supply for Riga city than the water consumption 122 thous.m³ day⁻¹ can be provided using only groundwater sources. However, then the water distribution network reliability and safety issues shall be solved optimising water reservoir volumes and their distribution within the supply network, as well as provision of sufficient number of water mains and adequate water pressure in the network. Study also showed that there is possibility in future to optimise number of wells in Quaternary aquifer using borehole pumps instead of relatively high number of wells used at the moment in syphons.

**Table 8.** Summary on yields of water sources (thous.m³ day⁻¹) of water supply scenarios for the eastern and western parts of Riga (RE and RW).

| Scenario No | Total yield (thous.m³ day⁻¹) | Yield (thous.m³ day⁻¹) of water source | Transfer RW → RE (thous.m³ day⁻¹) |
|-------------|-----------------------------|---------------------------------------|----------------------------------|
| 1           | 124.7                       | 63.6/61.1                             | 26.9                             |
| 2           | 122.9                       | 31.8/91.1                              | -3.1                             |
| 3           | 122.6                       | 30.0/92.6                              | -4.6                             |
| 4           | 122.6                       | 0.0/122.6                              | -34.6                            |
| 5           | 122.0                       | 0.0/122.0                              | -34.0                            |

*if RE water consumption is 88.0 thous.m³/day*
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