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Assessing the Impact of the Promising Technical Groundwater Intake Operation on the Usolka River Surface Runoff

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Оценка влияния эксплуатации перспективного технического водозабора подземных вод на поверхностный сток р. Усолки

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Groundwater production may be accompanied by negative impacts on the environment. The most significant environmental consequences of groundwater withdrawal, in addition to the depletion of its reserves, a decrease in its level and the formation of depression craters, is a change in the relationship between groundwater and surface runoff and, as a consequence, a decrease in the volume of river flow when aquifers are depleted. To eliminate the negative impact of groundwater extraction on natural ecosystems, it is necessary to take into account the natural resources of groundwater, their relationship with surface runoff, and provide predictive estimates of the water balance of the territory as a result of technogenic impact.

The purpose was to study the distribution of natural groundwater resources within the study area and assess the impact of groundwater withdrawal on the surface runoff of the river Usolka when organizing industrial and technical water supply to oil production facilities.

The objects of the study were the groundwater of the weakly aquiferous locally aquiferous Sheshminsky terrigenous complex confined to the river basins Malaya Alenka, Bolshaya Alenka, Bezymyanny stream, as well as the watercourses themselves, which are left-bank tributaries of the river Usolka.

As a result, the minimum flows of various supply levels of the left bank tributaries of the river Usolka were determined: Bezymyanny stream, river Malaya Alenka, river Bolshaya Alenka. The most water-abundant zones were identified and the magnitude of natural groundwater resources of the weakly aquiferous, locally aquiferous Sheshminsky terrigenous complex was established. The possibility of organizing industrial and technical water supply using groundwater without affecting the river Usolka flow was proven.

Ключевые слова:
оценка влияния, минимальный сток, естественные ресурсы, подземные воды, шешминский терригенный комплекс, река-аналог, техническое водоснабжение, Пермский край.

Добыча подземных вод может сопровождаться негативным воздействием на окружающую среду. Наиболее значительными экологическими последствиями отбора подземных вод, помимо истощения их запасов, снижения их уровня и образования депрессионных воронок, является изменение взаимосвязей между подземными водами и поверхностным стоком и, как следствие, уменьшение объема речного стока при истощении водоносных горизонтов. Для исключения негативного влияния на природные экосистемы добычи подземных вод необходимо учитывать естественные ресурсы подземных вод, их взаимосвязь с поверхностным стоком и давать прогнозные оценки водного баланса территории в результате техногенного воздействия.

Целью исследования являлось изучение распределения естественных ресурсов подземных вод в пределах изучаемой территории и оценка влияния водоотбора подземных вод на поверхностный сток р. Усолки при организации производственно-технического водоснабжения объектов нефтедобычи.

Объектами исследования являлись подземные воды слабоводоносного локально-водоносного шешминского терригенного комплекса, приуроченные к бассейнам р. Малая Аленка, р. Большая Аленка, ручей Безымянный, а также сами водотоки, которые являются левобережными притоками р. Усолки.

В результате были определены минимальные стоки различной обеспеченности левобережных притоков р. Усолки: Безымянный ручей, р. Малая Аленка, р. Большая Аленка. Выделены наиболее водообильные зоны и установлена величина естественных ресурсов подземных вод слабоводоносного, локально-водоносного шешминского терригенного комплекса. Доказана возможность организации производственно-технического водоснабжения за счет подземных вод без влияния на речной сток р. Усолки.

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Introduction

Groundwater extraction can have a negative impact on the environment. The most significant environmental consequences of groundwater withdrawal, in addition to the depletion of groundwater reserves, recession of their level and the formation of depression funnels, are changes in the relationship between groundwater and surface runoff and, as a result, loss of river flow volume due to the aquifers depletion. To exclude negative influence on natural ecosystems of groundwater extraction it is necessary to take into account the natural resources of groundwater, their relationship with surface runoff, and to give predictive estimates of the water balance of the territory as a result of anthropogenic environmentsl impact.

The problem of the impact of groundwater withdrawal on river flow is associated with a significant increase of such withdrawal and development of river flow change, the creation of water resources accounting and management systems. There are a number of examples of the negative impact of groundwater withdrawal in the Moscow Artesian Basin (MAB) [1], on the territory of the Kursk Magnetic Anomaly (KMA) [2, 3], on the eastern slope of the Northern and mountain-folded Urals [4], in Belarus [5–7], and in Ukraine [8]. Examples of the impact of groundwater withdrawal on river flow are also known abroad (in England, Germany, India, Spain, the USA, and France) [9–17].

The assessment of the impact of groundwater intake operation on river runoff is carried out using various hydrological, water-balance, indicator, and hydrodynamic methods. This problem and its importance in the solution of hydrogeological and water management problems was firstky considered by E.L. Minkin [18–21]. Later, together with S.Y. Kontsebovsky, a number of analytical solutions were proposed [22–24]. Various aspects of the impact of groundwater withdrawal on river flow were dealt with by V.D. Babushkin, B.V. Borevsky [25–26], F.M. Bochever [27–29], R.V. Bulatov [30], N.N. Verigin [31, 32], V.D. Grodzensky [33], I.S. Zektser [34–36], V.A. Zlotnik [37], V.S. Kovalevsky [38], N.N. Lapshin, V.S. Sarkisyan, V.S. Ustyuzhanin, M.A. Khordikainen [33], I.S. Zektser [34–36], V.A. Zlotnik[37], V.S. Kovalevsky [38], N.N. Lapshin, V.S. Sarkisyan, V.S. Ustyuzhanin, M.A. Khordikainen [39, 40], M.G. Khublaryan [41, 42], K.N. Tsyganova [43], V.M. Shestakov [44, 45], S.O. Grinevsky, R.S. Shtengelov [46–48], L.Y. Yazvin [49–50] and others. Abroad the problems of the influence of groundwater withdrawal on river flow were first studied by S. Theis [51], later by R. Glover and G. Balmer [52], most fully by M. Hantush, as well as by J. Bredehoeft, R. Young [53], L. Conrad, S. Beljin [54], In. Hunt [55], N. Kiel [56], R.-F. Lelievre, P. Peaudecerf, R. Prudhomme [57], Th. Maddock, N. Bouwer [58-59], R. Manson [60], R. Saxena, Chandra Satish [61], R. Wardlaw, G. Fleming [62], C. Wright [63] and others.

L.S. Yazvin, S.L. Pugach, V.D. Grodzensky, MA Hordikainen et al. (VSEGINGEO), for the purposes of compiling reporting water balances during the state water cadastre, developed averaged coefficients of interconnection (attracting river water during the operation of groundwater intakes), which consider the used aquifers and the location of water intakes in relation to rivers for 220 design sections of the main rivers [64].

Within the study area, it is planned to organize industrial and technical water supply to oil production facilities at the expense of groundwater of low-water, locally aquiferous Sheshminsky terrigenous complex. To assess the possibility of obtaining the operational flow rate of wells in the amount of 630 m^3/day, hydrological service works were carried out, as a result of which natural groundwater resources were determined and the impact of groundwater withdrawal on the surface runoff of the Usolka River was assessed.

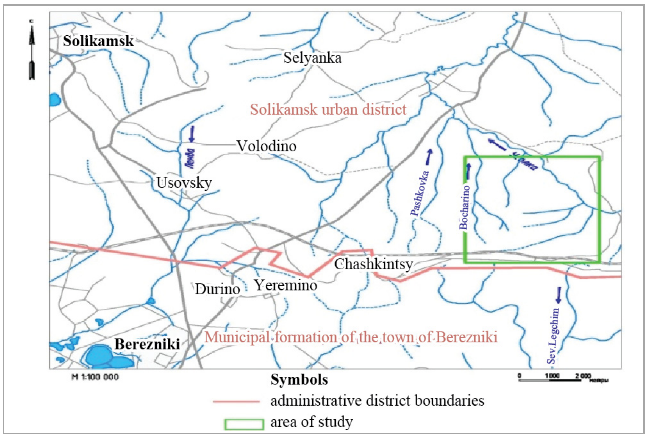

Fig. 1. Base map of the studied area

The purpose of this research was to study the distribution of natural groundwater resources within the investigated area and to assess the impact of groundwater withdrawal on the surface runoff of Usolka River during the Organization of Industrial and Technical Water Supply of Oil Production Facilities.

The objects of the study were groundwater of the low-water, locally aquiferous, Sheshminsky terrigenous complex, confined to the basins of the Malaya Alenka River, the Bolshaya Alenka River, the Bezymyanny Stream, as well as the watercourses themselves, which are left-bank tributaries of the Usolka River.

The main objectives of the study were:

- determination of the hydrological characteristics of the studied watercourses (intra-annual distribution of flow of different availability, determination of the minimum flow of 50 %, 95 % availability);
- calculation of natural groundwater resources;
- assessment of the impact of underground water intake on the flow of the Usolka River.

General information about the area of study

The area of study is located in the northern part of Perm Krai on the territory of Solikamsk urban district (Fig. 1).

The river network of the district is an integral part of the Kama River basin. In the north-eastern part of the district the main watercourse is the Usolka River with Bol. and Mal. Alenki tributaries and Bezymyanny stream.

In the annual recharge of watercourses snow water is of predominant importance - up to 56 %, rainwater – 20 %, groundwater – 24 %. The ratio of underground and surface components of runoff varies significantly according to the seasons. In spring,the share of groundwater runoff is small - on average 10-15 % of the total runoff per season. In surface runoff (85–90 %) practically exclusive role belongs to meltwater, since during the spring flooding rainfall, as a rule, is insignificant.

The total runoff during the summer-autumn low-water period consists of 50–60 % of the surface and 40–50 % of the underground runoff. In winter, watercourses are recharged by groundwater reserves.

The peak of the spring flood can be attributed to mid-April - early May. Its duration is about 10-25 days. At the same time, the rise in levels (on small rivers) reaches 2 m and more. The flood fall is usually longer and is often accompanied by rainfall floods.

Autumn floods on small rivers occur annually, while the rise in levels is 1-3 m above the low water. Their duration ranges from 10 days to 2 months (average duration is about one month).

In winter, in the absence of atmospheric nutrition, the level regime in the rivers becomes stable and is characterized by a gradual decrease up tol the spring flood. At the work site the minimum water level in the Usolka River reaches the actual elevation of 152.5 m.

Ice-forming processes on rivers begin with the appearance of lard, slush, banks in late October - early November. The average freezing date of rivers is November 20. Rivers usually break up in the last ten days of April – the first ten days of May. Clearance of the rivers from ice occurs 3-10 days later.

The climatic characteristics of the studied area are given from Solikamsk and Berezniki meteorological stations of Perm Krai.

The climate of the territory under consideration is continental, with cold long winters, warm, but relatively short summers, early autumn and late spring frosts. In winter, an anticyclone with highly cooled air is often observed in the Urals. Cooling of the air in anticyclones occurs mainly in the lower layers; at the same time the moisture content of these layers decreases, the air temperature in winter usually increases with altitude, as a result it is formed thick layers of inversion.

The main indicators of the temperature regime are the average monthly, maximum and minimum air temperatures.

The average annual air temperature is plus 1.3 ˚C.

The coldest month of the year is January with an average monthly air temperature of minus 15.4 ˚C according to the Berezniki weather station, the warmest is July with an average monthly temperature of plus 17.8 ˚C (w/s Solikamsk) and 24.2 ˚C (w/s Berezniki).

The absolute minimum air temperature reaches minus 48 ˚C, the absolute maximum is plus 37 ˚C.

The onset of stable frosts occurs on average on November 5, the cessation is on March 23; The duration of stable frosts is 139 days.

The duration of the frost-free period is on average 101 days. The first frosts in the territory under consideration are observed on average on September 12, the last - on June 2.

The relative humidity is greatly influenced by the relief forms, the proximity of water bodies, forests, etc. The average annual relative humidity in the area was 76 %. The maximum average monthly relative humidity in the region is observed in January, December – 85 %, the minimum – 61 % - in May.

The maximum precipitation per month is observed in July - 84 mm, the minimum - in February - 28 mm. The amount of solid precipitation in November - March is 182 mm, liquid for the period April - October - 465 mm.

Snow cover is one of the most important factors affecting the formation of the climate. The average of the highest snow cover heights in the open (field) area is 60 cm, the maximum height of the snow cover is 81 cm, the minimum is 34 cm.

Methods of research and factual material

The studied stream flows are rivers:

Bolshaya Alenka, Malaya Alenka, Nameless Stream.

A network of hydrometric recording stations was organized on the explored stream flows (Fig. 2):

– St. 1 – Usolka-post Belsky river (analogue river);

– St. 2 – Bezymyanny Creek River, mouth – left tributary of the Usolka River;

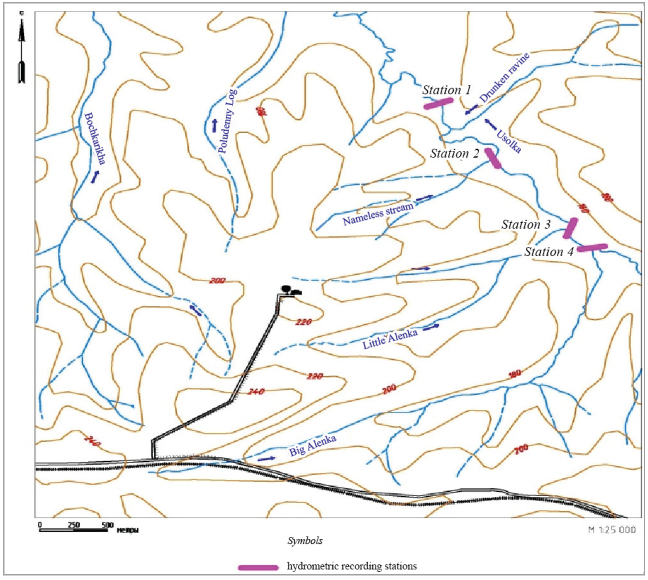

Fig. 2. Location of hydrometric network of recording stations

– St. 3 – mouth of the Little Alenka is a left tributary of the Usolka River;

– St. 4 – mouth of the Big Alenka is a left tributary of the Usolka River.

Considering the tight time frames of work (12 months) and insufficient data on the explored stream flows the recommended method of hydrological analogy was widely used in the study to calculate the required characteristics of runoff. The analogue was selected according to the recommendations of SR 33-101-2003 [65]. The Usolka River is taken as an analogue – Belsky village.

Hydrological characteristisc of this stream flow are as follows: minimum flow of 95 % availability $Q_{95\%}$ = 0,11 m^3/s; minimum flow of 50 % availability $Q_{50\%}$ = 0,13 m^3/s; minimum underground flow module of 95 % availability $M_{95\%}$ = 4,05 m^3/s; minimum underground flow module of 50 % availability $M_{95\%}$ = 3,30 m^3/s. Annual flow of 95 % availability was Q_{year} = 0,28 m^3/s, maximum flow rates $Q_{\max 1\%}$ = 17,5 m^3/s. Intra-annual flow distribution along section No. 1 of the river Usolka - Belsky village is given in Table 1 [66].

The calculation of the minimum flow of the Bezymyanny Ruchey, Malaya Alenka, Bolshaya Alenka rivers and the natural groundwater resources of the studied sream flow is calculated by the results of direct measurements of water discharges at stations No 1–4.

According to the results of measurements of water discharge at river cross-sections, the calculation of the transient coefficients of the flow of the studied rivers and the analogue river was carried out according to the formula (1):

$$K = \frac{Q_2}{Q_1}, \qquad (1)$$

where Q_2 – discharge of the studied stream flow, m^3/s; Q_1 – discharge of the river-analogue, m^3/s.

Due to the fact that the minimum runoff is 40 % of the average annual flow in the analogue river, the average annual flow of the studied stream flows is determined by the formula (2):

$$Q_{\text{av.annual}} = \frac{Q_{\min}}{0,4}, \qquad (2)$$

where Q_{min} – minimal runoff, m^3/s.

Table 1

Intra-annual distribution of runoff along the station No 1

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual runoff	Average annual runoff
r. Usolka – v. Belsky,%													
3.8	3.2	3.6	23.4	16.2	9.6	5.3	5.1	6.4	7.8	9.3	6.3	100	–
r. Usolka – v. Belsky, $Q_{50\%}$ (m^3/s)													
0.15	0.13	0.14	0.93	0.64	0.38	0.21	0.20	0.25	0.31	0.37	0.25	3.96	0.33
r. Usolka – v. Belsky, $Q_{95\%}$ (m^3/s)													
0.13	0.11	0.12	0.79	0.54	0.32	0.18	0.17	0.22	0.26	0.31	0.21	3.36	0.28

Table 2

Intra-annual distribution of runoff across the studied stream flows

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual flow	Average annual flow
r. Nameless stream, $Q_{50\%}$ (m^3/s)													
0.009	0.008	0.009	0.056	0.039	0.023	0.013	0.012	0.015	0.019	0.022	0.015	0.24	0.020
r. Little Alenka, $Q_{50\%}$ (m^3/s)													
0.007	0.006	0.006	0.042	0.029	0.017	0.010	0.009	0.012	0.014	0.017	0.011	0.18	0.015
r. Big Alenka, $Q_{50\%}$ (m^3/s)													
0.027	0.023	0.026	0.168	0.117	0.069	0.038	0.037	0.046	0.056	0.067	0.045	0.72	0.060
r. Nameless stream, $Q_{95\%}$ (m^3/s)													
0.008	0.007	0.008	0.051	0.035	0.021	0.011	0.011	0.014	0.017	0.020	0.014	0.22	0.018
r. Little Alenka, $Q_{95\%}$ (m^3/s)													
0.005	0.005	0.005	0.034	0.023	0.014	0.008	0.007	0.009	0.011	0.013	0.009	0.14	0.012
r. Big Alenka, $Q_{95\%}$ (m^3/s)													
0.024	0.020	0.022	0.146	0.101	0.060	0.033	0.032	0.040	0.049	0.058	0.039	0.62	0.052

Table 3

Discharge characteristics of the studied stream flows

River	F, km^2	Q_{50}, m^3/s	M$_{50}$,l/s·km^2	$Q_{95\%}$, m^3/s	M$_{95\%}$, l/s·km^2
Average annual discharge					
r. Nameless stream	1.30	0.020	15.4	0.018	13.8
r. Little Alenka	2.71	0.015	5.54	0.012	4.43
r. Big Alenka	4.66	0.060	12.9	0.052	11.2
Maximum water consumption					
r. Nameless stream	1.30	0.69	530	0.100	77.2
r. Little Alenka	2.71	1.44	530	0.272	77.2
r. Big Alenka	4.66	2.47	530	0.468	77.2
Minimum discharge					
r. Nameless stream	1.30	0.008	6.15	0.007	5.38
r. Little Alenka	2.71	0.006	2.21	0.005	1.85
r. Big Alenka	4.66	0.024	5.15	0.021	4.51

Maximum runoff is determined by the formula (3):

$$Q_{\max} = \frac{M_{\max} \cdot F}{1000}, \qquad (3)$$

where $M_{\max}$ – maximum groundwater flow modulus, l/s·km^2, F – flood area, km^2.

The groundwater flow modulus is calculated by the formula (5):

$$M = \frac{Q}{F}, \qquad (4)$$

where Q – water consumption, m^3/s, F – flood area, km^2.

Results and discussion

As a result of water flow measurements in sections No 1–4 and office processing of initial data the hydrological characteristics of the studied stream flows were obtained and presented in Table 1.

Analysis of the data of the Table 2 shows that the study area is in the zone of sufficient moisture. Two periods (spring floods and summer-autumn rains) provide powerful groundwater recharge.

It should be noted that the maximum discharges are overestimated, since at high floods there is a release of water to the floodplain, which leads to a decrease in runoff. At the same time, this value does not affect the

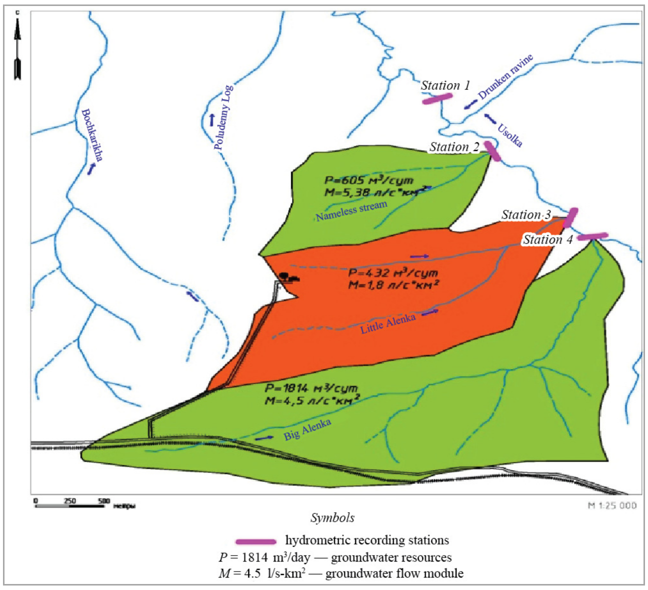

Fig. 3. Distribution of resources and modules of groundwater flow in the study area

calculation of natural groundwater resources, and it is quite sufficient for assessment.

The calculation of natural groundwater resources was carried out for individual sections of the basins of the tributaries of the Usolka River for 95 % availability.

Natural resources are controlled by minimum flow. Resources of the studied sites of 95 % availability (P = 95 %): one section of the river Nameless Stream – Qe = 0.007 m^3/s, or 605 m^3/day; the second section of the river Little Alenka - Qe = 0.005 m^3/s, or 432 m^3/day; the third section of the Big Alenka = 0,021 м^3/s, or 1814 m^3/day. The total amount of calculated inferred resources will be 2.8 thousand m^3/day.

The basin of the Little Alenka river should be considered as the most unpromising in terms of the resource potential of the territory. Its underground flow modulus is 2.5 times less than the module of the Big Alenka river section and 3 times smaller than the module of the section of the Nameless Stream river. At the same time, the first section, the Nameless Stream river, with the highest groundwater flow module for the district, M95 = 5.38 l/s·km^2, is the most abundant.

It should be noted that it is possible to carry out calculations for such small areas on the basis of such a short period of observation, but it is not always correct. The results of calculations based on the obtained absolute values may contain a large number of errors associated with both objective factors and system errors in measurements. At the same time, the relative values of the obtained modules are quite reliable and realistic, when general and characteristic errors or errors are leveled relative to each other. In any case, the basin of the Little Alenka should be considered as the most unpromising in terms of the resource potential of the territory. Its underground flow modulus is 2.5 times less than the module of the Big Alenka river and 3 times smaller than the module of the section of the Nameless Stream River. Subsequently, the high water abundance of the Sheshminsky rocks in the area of study was confirmed by the drilling results.

The distribution of natural resources and groundwater flow modules is shown in Fig. 3. In addition, the impact of groundwater abstraction on the surface flow regime of the Usolka River was assessed, since the part of its flow forms the operational reserves of the Usolskoye drinking groundwater deposit.

The analysis of possible influence of water intake operation on river flow is given according to the scheme:

– full impact;

– with consideration of the operating experience of existing water intakes.

To assess the possibility of the influence of water withdrawal from groundwater, we will take the flow rate of the water intake groundwater in the amount of 630 m^3/day (0.0073 m^3/s). Hydrological characteristics of the Usolka River: minimum flow of 95 % availability $Q_{95\%}$ = 0.11 m^3/s; minimum flow of 50 % availability $Q_{50\%}$ = 0.13 m^3/s; Minimum annual flow of 95 % availability Q_{year} = 0.28 m^3/s. Thus, the remaining flow at a water withdrawal of 0.0073 m^3/s will be: minimum flow of 95 % availability $Q_{95\%}$ = 0.103 m^3/s (estimated impact 6.4 %); minimum flow of 50 % probability $Q_{50\%}$ = 0.123 m^3/s (estimated impact 5.4 %); minimum annual flow of 95 % availability Q_{year} = 0.273 m^3/s (estimated effect 2.5 %). Thus, even taking into account the full impact of the water intake on the river flow, the flow rate of the river Usolka will not practically change.

In [68] the impact of water intake 'Usolka' on the river flow was assessed, which showed that the impact is not 100 %, but within 40-50 % (and this is at water intake with a flow rate of 60-70 thousand m^3/day).

Thus, for the area of study the impact will be no more than 2.7-3.2 % (for minimum flow) P = 50-95 %.

Conclusion

In order to organize industrial and technical water supply to oil production facilities located in the Solikamsk urban district of Perm Krai the resource potential of groundwater of the low-water, locally aquiferous Sheshminsky terrigenous complex was assessed. Groundwater resources are determined by the minimum flow of 95 % of availability by analogy. Groundwater resources even under the most severe conditions (P = 95 %) are: Nameless Stream River – 605 m^3/day; Little Alenka river – 432 m^3/day; Big Alenka river – 1814 m^3/day. The total amount of calculated inferred resources will be 2.8 thousand m^3/day, which is much higher than the declared demand (630 m^3/day). Based on the results of the work, the most water-rich section was allocated - the Nameless Stream with the highest underground flow module for the district M95 = 5.38 l/s·km^2. The impact of groundwater intake operation on the surface runoff of the Usolka River was also assessed. It has been proved that groundwater extraction will not have any significant impact on the Usolka River. Thus, it can be concluded that it is possible to organize industrial and technical water supply at the expense of groundwater of the Sheshminsky aquifer complex with a declared need of 630 m^3/day.

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