

Rimma Abdrashitova ¹
Yulia Salnikova
Andrey Plavnik
Yulia Sretenskaya
Xiaopu Wang
Victoria Kolotygina
Mikhail Poluyanov

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PRESERVATION OF GROUNDWATER QUALITY IN APT-ALB-CENOMANIAN AQUIFER COMPLEX UNDER CONDITIONS OF LONG-TERM OIL AND GAS TECHNOGENESIS IN SHIROTNOE PRIOBIE REGION OF WESTERN SIBERIA

Abstract: *This study assessed the preservation of water quality in the Apt-Alb-Cenomanian aquifer complex (AAC AC) under conditions of long-term multidirectional oil and gas technogenesis. This involves two opposing processes: groundwater extraction to maintain reservoir pressure in productive horizons, and the injection of excess produced water into the complex. The scale of each of the above processes reaches hundreds of thousands of cubic metres of water per year.*

The AAC AC in the West Siberian oil and gas region belongs to the Mesozoic hydrogeological basin. To achieve this goal, data on the three largest oil fields were used.

The research methodology involved the systematization of historical and current water quality data. The study found that, despite the significant anthropogenic load, the natural hydrogeochemical equilibrium in the system “water-rock” of the studied AAC AC remains largely intact.

Keywords: *oil and gas hydrogeology, groundwater, oil field, reservoir pressure maintenance, water mineralization, produced water, filtration-capacity properties, absorbing horizon petroleum technogenesis.*

1. Introduction

The purpose of the study is to assess the water quality of the Apt-Alb-Cenomanian aquifer complex (AAC AC) under the influence of longstanding multidirectional processes: groundwater extraction for reservoir pressure maintenance (RPM) in productive oil horizons and injection of excess associated water.

The adverse effects of hydrocarbon extraction on the subsurface hydrosphere have been observed in various oil and gas producing

regions of the world. Any oil operation poses an unavoidable risk to water resources (Zabbey & Olsson, 2017), in the case of RPM system operation or disposal of excess produced water, we are dealing with direct impacts on aquifer complexes. Companies across the globe in hydrocarbon exploration and production face a number of challenges in managing the associated water resources generated in significant quantities: globally, the average water cut of production has increased to almost 75% (Ali & Hascakir, 2015). In some fields in Western Siberia, this figure is as high as 95%. Within the Khanty-

¹ Corresponding author: Rimma Abdrashitova

Email: abdrashitovarn@tyuiu.ru

Mansiysk Autonomous District of the Tyumen Region of Russia, which includes the Shirotnoye Priobye, the total volume of produced water injected into the studied AAS VC over the last decade was 196.2 million m³, the total volume of water extracted from the AAS VC was 372.9 million m³ (Salnikova, 2021).

Associated water is generally not clean enough for direct use and is therefore traditionally considered a waste (Veil, 2011; Jiménez et al., 2018; Mishra et al., 2023.). Thus, we observe the formation of new groundwater quality indicators within any absorption horizon, including AAC AC, by mixing formation water and produced water. It should be understood that in associated water, before it is utilised in the subsurface, a whole cascade of chemical reactions occurs when it is lifted to the earth's surface to separate hydrocarbons due to changes in thermobaric conditions and the impact of oilfield reagents.

At present, the recognised viewpoint is that the safest way to utilise produced water in oil and gas producing regions is injection into absorbing horizons (Eyitayo et al., 2024; Abdrashitova et al., 2022; Salnikova, 2021). At the same time, the absorbing horizon should meet the requirements of the current regulatory documents. Despite the fact that utilisation of associated water into absorbing horizons is less dangerous than discharge into surface water bodies, this method can also have a significant impact on the state of the hydrosphere (Barreto & Schiozer, 2012), and, accordingly, on the quality indicators of natural formation waters.

Researchers involved in the management of produced water resources point to the need to improve technologies to control the use of these waters and their impact on the natural hydrosphere.

This paper uses data on the three largest oil fields in the Shirotnoye Priobie region of Western Siberia: Zapadno-Ust-Balykskoye, Megionskoye and Taylakovskoye. The studied fields have been exploited since the

60s, i.e. more than 50-60 years. At the first stages of field development, no RPM was required and oil production was carried out without water injection into productive formations. But since 1967 at the Megionskoye field, since 2006 at the Taylakovskoye field and since 2011 at the Zapadno-Ust-Balykskoye field, water has been injected into the productive intervals of the section for RPM. For this purpose, water is extracted from the AAC AC. In parallel with the operation of the RPM system, the oil water cut has been growing, and since 2015 the volume of excess mineralised water separated from oil (which is called "associated water") has reached the volumes to be utilised. Thus, during the last decades we observe a peculiar "cycle" (Figure 1) of mineralised, anthropogenically altered waters in the Mesozoic hydrogeological basin, which led to the transformation of the AAS VC water quality indicators and redistribution of the component composition of waters and formation pressures of the investigated complex (Kurchikov et al., 2020; Abukova & Volozh, 2021). Water from the AAC AC enters the underlying productive horizons of the Neocomian and Jurassic ages, and associated water enters the AAC AC.

In this regard, careful monitoring of the quality of AAC AC waters is highly relevant. Water sampling from the AAC AC by subsoil users, according to the normative documents in force in the Russian Federation ("Procedure for keeping records by the owners of water bodies and water users of the volume of water resources intake (withdrawal) from water bodies and the volume of wastewater, including drainage water, and their quality", OST 39-225-88 "Water for waterflooding of oil reservoirs. Quality requirements"), is performed once every 4 months, with an additional 1 control sample taken during the year. Thus, in order to track changes in the quality of AAC AC water, the groundwater monitoring organisations have at their disposal 5 samples per year. This is very little. But in the presence of long-term continuous

observations (more than 10 years) even this amount of data allows to draw conclusions about general trends of changes in water quality of AAC AC. In this study we have

analysed all existing long-term data on monitoring of water quality of AAC AC at Zapadno-Ust-Balykskoye, Megionskoye and Taylakovskoye oil fields.

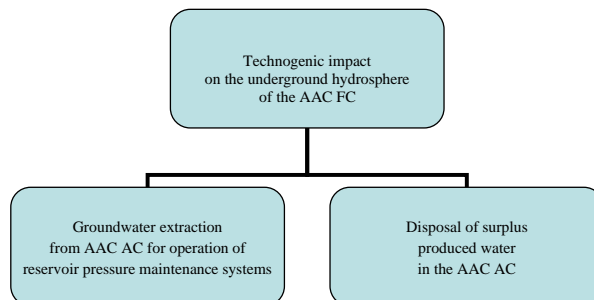


Figure 1. Directions of anthropogenic impact on the water quality of the AAC AC

The following tasks were accomplished during the study to confirm the proposed hypothesis:

1. analysis of the geological structure and, in particular, filtration-capacity properties of AAC AC rocks within the boundaries of the Zapadno-Ust-Balykskoye, Megionskoye, and Taylakovskoye fields;
2. systematization and collection of data on volumes of water withdrawal from the AAC AC to provide RPM and on volumes of disposal of surplus produced water in the AAC AC;
3. analyses of changes in groundwater quality of AAS VC based on the results of long-term monitoring.

The above tasks represent the structural subheadings used in the Methods, Results, and Discussion sections.

2. Materials and Methods

2.1. Geological structure and filtration-capacity properties of AAC AC formations

The Megionskoye, Zapadno-Ust-Balykskoye, and Taylakovskoye fields belong to the central part of the West Siberian megabasin (WSMB) – Shirotnoye Priobie.

The AAC AC (K1a12+K2cm, K1a11, K1ap) belongs to the Mesozoic WSMB basin (Figure 2). The Mesozoic basin includes the Neocomian, Berriasian-Valanginian, and Jurassic complexes containing oil deposits. The Mesozoic basin is central to the WSMB section (Matusevich et al., 2016), overlain by the Cenozoic basin above and underlain by the Paleozoic basin below. The total thickness of the sedimentary cover of the WSMB in the area of the considered fields is more than 3 km.

The studied AAC AC is developed in the facies of the Pokur Formation and is lithologically represented by irregular alternation of compacted sands, sandstones, and siltstones with interlayers of clays, with a total thickness of about 800 m.

According to regional data in natural conditions, absolute marks of piezometric levels in the works area vary from +65 to +45 m.

Since the studied fields belong to the inner hydrogeological zone of the WSMB, the filtration-capacity parameters of reservoirs within the three fields have close values of porosity (from 26.1 to 29.4%) and permeability (0.163–0.530 μm^2). The effective thickness of the AAC AC averages 370 m (values determined by the results of interpretation of hydrodynamic studies of

water intake wells). Waters are high-pressure, water availability of AAC AC rocks is the highest in the Mesozoic basin. Discharges of water intake wells in the area of AAC AC spreading can reach 1–2 thousand m³/day at depressions up to 100–150 m on average.

Mineralogically, the AAC AC reservoirs represented by sandstones are dominated by quartz (38 to 70%), feldspars (18 to 40%), clay minerals (0 to 40%), and carbonates (up to 23%) in some samples.

From the Cenozoic hydrogeologic basin containing drinking groundwater, the aquifers of the AAC AC are reliably overlain by water-bearing rocks of Lower Cretaceous age (K₂t-d). The thickness of these waterproof rocks, represented by clays and siltstones, reaches 770 meters.

The AAC AC is isolated from the Neocomian, Berriasian-Valanginian, and Jurassic reservoirs, which are productive by a thick thickness of watertight rocks (up to 250 m).

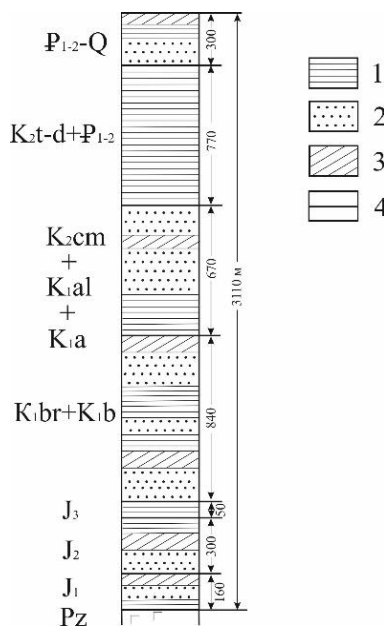


Figure 2. Typical geological section of the central part of the WSMB:
1 – clay sediments; 2 – sandy sediments; 3 – clay-siltstone sediments

Waters have sodium chloride ion-salt composition, belonging to the chloride-calcium type according to V.A. Sulin (rNa/rCl=0.9). The value of mineralization of AAC AC waters on average in the study area is 18.2 g/dm³. The active water medium is neutral, less often slightly acidic, or slightly alkaline (average pH is 7.6). Water density is 1,005–1,020 g/cm³.

The main salt-forming components are sodium+potassium (4,293.0–7,527.9 mg/dm³) and chlorine (7,932.0–14,537.0

mg/dm³) ions. Calcium was found between 337.5 and 1,353.0 mg/dm³, magnesium between 56.9 and 182.4 mg/dm³, and hydrogen carbonate between 85.4 and 561.0 mg/dm³. The waters are virtually free of sulfates and carbonates.

The following microcomponents are determined in most cases: iodine – 9.0–19.5 mg/dm³, bromine – up to 31.7–70.0 mg/dm³, total iron – mostly units – first tens (21.7 mg/dm³).

2.2. Data on AAC AC water withdrawal volumes for RPM system operation and on volumes of produced water surplus utilization in AAC AC

Data on AAC AC water withdrawal volumes for RPM system operation and volumes of produced water surplus utilization are presented separately for each of the studied fields.

Data on AAC AC water withdrawal volumes to ensure RPM system operation Zapadno-Ust-Balykskoye field

Groundwater extraction to supply the RPM system at the Zapadno-Ust-Balykskoye field started in May 2011.

The underground technical water production volume during the operation period varied from 197.9 thousand m³ to 1,737.2 thousand m³ (Figure 3). At present, the accumulated volume of water extracted from the AAC AC is 14,709 thousand m³.

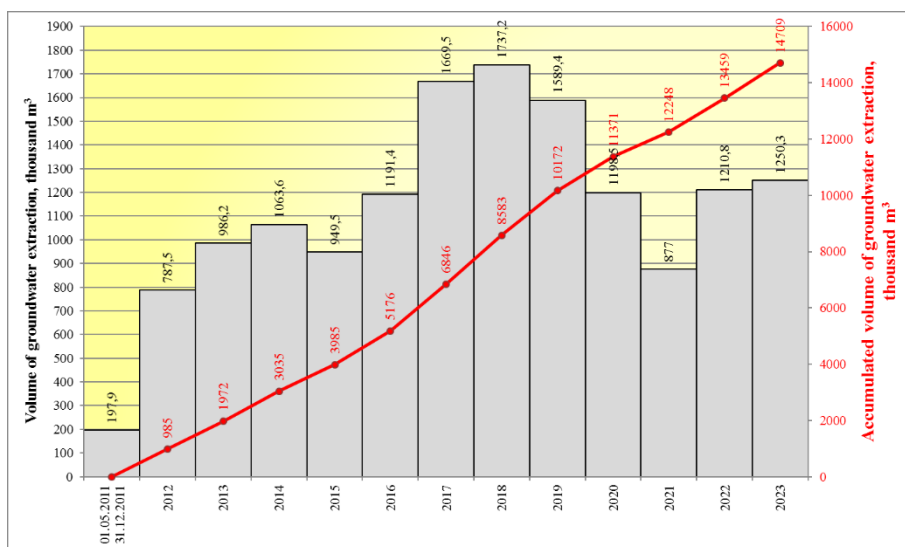


Figure 3. Dynamics of groundwater extraction of the AAC AC at the Zapadno-Ust-Balykskoye field

Megionskoye field

At the Megionskoye field, production of underground technical water to support the RPM system began in 1967. Annual groundwater extraction volumes and average water withdrawal capacity were recorded at the field from 1967 to 1980. From 1981 to 2004, the water intake area of the Megionskoye field was idle. As of September 2004, operation of the water intake site was

resumed. The water intake site was shut down again in 2020. The water intake was back in operation in 2022.

Generalized data on the dynamics of ground technical water production are presented in Figure 4. In total, 32,019 thousand m³ of reservoir waters were extracted from the deposits of AAC AC reservoirs during the considered period.

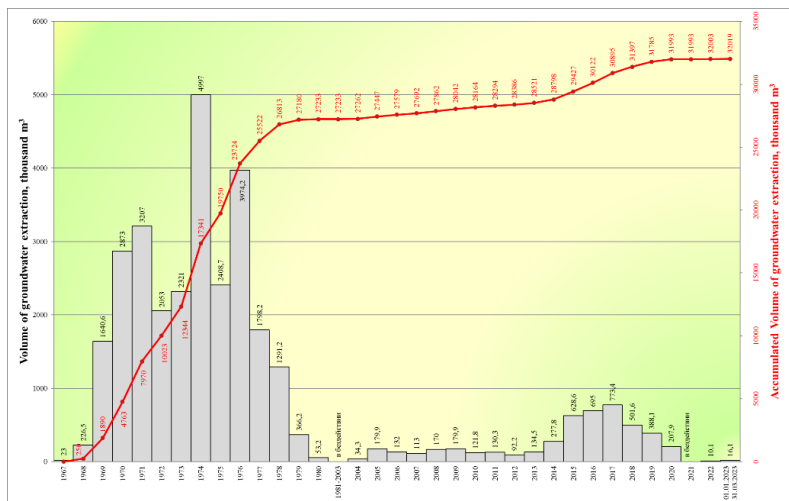


Figure 4. Dynamics of groundwater extraction of the AAC AC at the Megionskoye field

Taylakovskoye field

At the Taylakovskoye field, production of AAC AC groundwater for RPM purposes

began in May 2006. During the entire period of field operation, 55,189.4 thousand m³ of groundwater was extracted from AAC AC deposits (Figure 5).

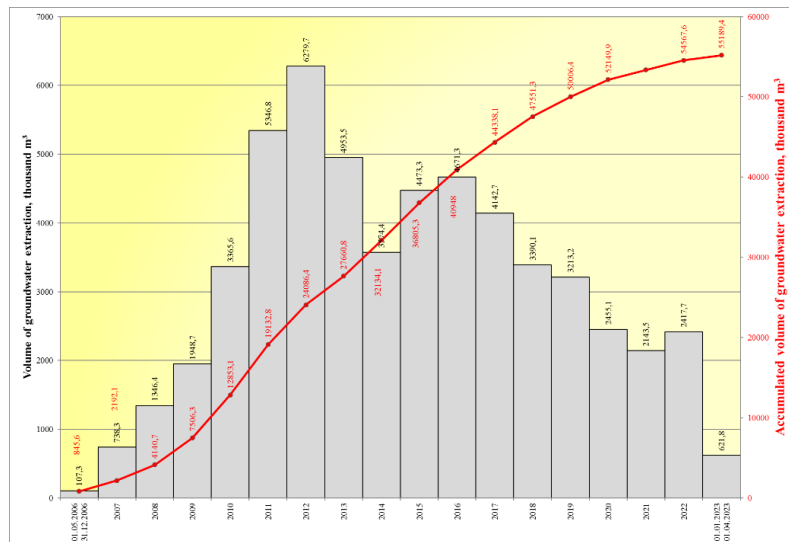


Figure 5. Dynamics of groundwater extraction of the AAC AC at the Taylakovskoye field

Data on volumes of the utilization of produced water surplus in the AAC AC

At hydrocarbon fields, from the beginning of the operation of disposal sites, the subsoil user keeps records of the volume of produced

water injection and water used for its own production and technological needs, which are recorded and entered into well logs, and then formed into monthly operational reports (MORs) or into reports (“Absorption well report”), which indicate the number of days

of operation, compacted discharges, fluid injection volumes by month, accumulated for the year and from the beginning of development for each well. MOR data are used by the subsoil user in the preparation of state reporting in the form of state statistical observation.

Zapadno-Ust-Balykskoye field

At the Zapadno-Ust-Balykskoye field since December 2015, injection of excess produced water into the AAC AC sediments has been carried out. A total of 10,715.1 thousand m³ of surplus produced water was injected into AAC AC sediments during the operation of absorption wells at the Zapadno-Ust-Balykskoye field (Figure 6).

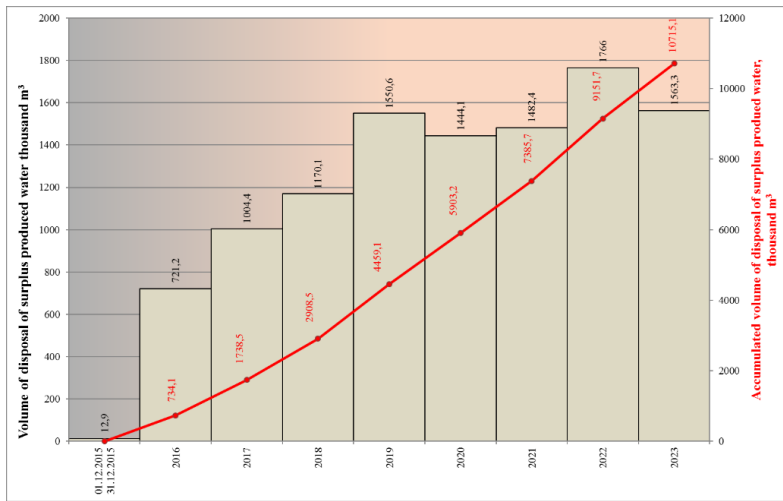


Figure 6. Dynamics of produced water surplus disposal at the Zapadno-Ust-Balykskoye field Taylakovskoye field

Megionskoye field

Injection of produced water and water used for own production and process needs at the

Megionskoye field started in March 2015 (Figure 7). The accumulated volumes of produced water surplus in the subsurface amounted to 16,152 thousand m³.

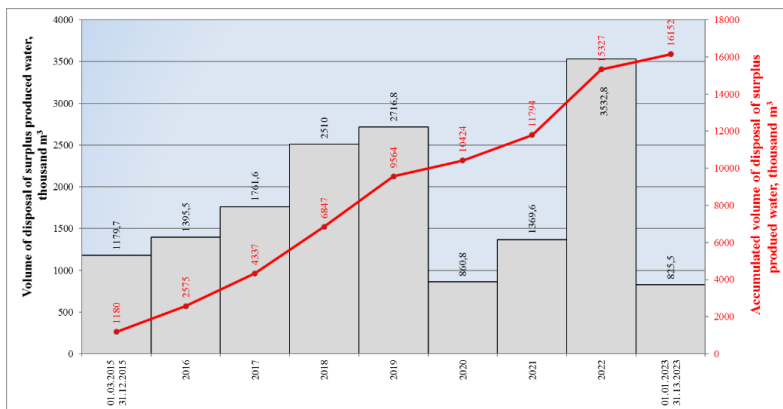


Figure 7. Dynamics of produced water surplus disposal at the Megionskoye field

Taylakovskoye field

The placement of excess produced water into the AAC AC sediments at the Taylakovskoye field has been carried out since November 2015.

During the considered period of operation, the volumes of produced water disposal into AAC AC sediments amounted to 4,516.7 thousand m³ (Figure 8).

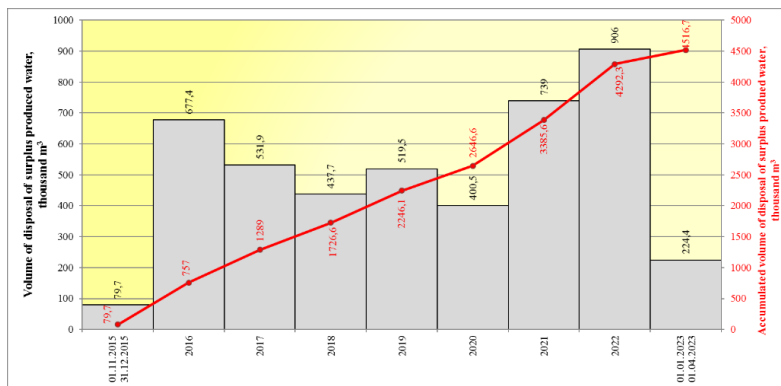


Figure 8. Dynamics of produced water surplus disposal at the Taylakovskoye field

2.3. Indicators of chemical composition of groundwater of the AAC AC according to the results of long-term monitoring

The entire period of operation of the studied fields was conditionally divided into 2 stages: Stage 1 – before RPM system operation (when oil production is due to the elastic mode of the deposit), Stage 2 – from the beginning of RPM system operation to the present time. Information on water quality of the AAC AC from the monitoring data was grouped and analyzed according to the specified stages.

For systematisation of data on Stage 1 all the results of 52 chemical analyses of AAC AC quality available to the subsoil user (in total for three fields) were used.

The natural hydrogeochemical characterization of AAC AC reservoir waters (Stage 1) for the three fields is summarized in Table 1.

Systematized information on chemical composition indicators of the AAC AC from the beginning of RPM system application is given in Table 2. The results of 1134 chemical analyses of the AAC AC were used to collect Stage 2 data.

Table 1. Hydrogeochemical parameters of reservoir water quality of the AAC AC before the RPM system was applied

Parameter name	Zapadno-Ust-Balykskoye field (1963–1967)	Megionskoye field (1970–1998)	Taylakovskoye field (1969–2005)
Anions, mg/dm ³			
HCO ₃ ⁻	85.4–378.2	109.8–305.1	170.8–314.7
Cl ⁻	9,511.8–12,566.7	8,865.2–12,407.5	9,645.0–11,562.2
CO ₃ ²⁻	n/a	n/a	n/a
SO ₄ ²⁻	n/a.–4.0	n/a.–12.0	n/a.–16.5
Cations, mg/dm ³			
Na ⁺ +K ⁺	5,771.4–7,527.9	5,108.3–7,157.6	5,528.0–7,106.7
Ca ²⁺	337.5–454.1	396.0–641.3	399.0–724.5

Table 1. Hydrogeochemical parameters of reservoir water quality of the AAC AC before the RPM system was applied (continued)

Parameter name	Zapadno-Ust-Balykskoye field (1963–1967)	Megionskoye field (1970–1998)	Taylakovskoye field (1969–2005)
Mg ²⁺	56.9–145.9	61.0–182.4	77.0–128.0
Br ⁻ , mg/dm ³	43.3–50.6	31.7–70.0	43.9–53.8
I ⁻ , mg/dm ³	15.7–19.5	9.0–11.3	11.0–16.1
Iron, mg/dm ³	0.8–1.5	0.1–21.7	7.8–11.3
Mineralization, g/dm ³	16.1–20.8	14.6–20.5	16.1–19.6
Hydrogen index, pH	7.5–8.4	6.5–8.3	7.0–7.3
Water density, g/cm ³	1.005–1.011	1.005–1.016	1.011–1.014
Water types, according to V.A. Sulin	Calcium chloride		
rNa/rCl metamorphosis coefficient	0.90–0.95	0.86–0.91	0.87–0.94
Number of samples studied (wells)	6 (4)	40 (14)	6 (3)

Table 2. Hydrogeochemical parameters of reservoir water quality of the AAC AC from the beginning of RPM system application until 2023

Parameter name	Zapadno-Ust-Balykskoye field (2011–2023)	Megionskoye field (1967–2023)	Taylakovskoye field (2006–2023)
Anions, mg/dm ³			
HCO ₃ ⁻	1.7–1111.0	79.0–403.0	73.2–964.1
Cl ⁻	8,501.0–13,116.5	8,865.0–15,421.0	8,508.0–13,826.0
CO ₃ ²⁻	n/a – 36.0	n/a	n/a – 90.0
SO ₄ ²⁻	n/a – 21.0	n/a – 2.0	n/a – 3.0
Cations, mg/dm ³			
Na ⁺ +K ⁺	4,756.0–8,017.8	4,995.0–8,790.0	4,797.8–8,234.0
Ca ²⁺	100.2–840.0	320.7–1,302.0	180.4–982.0
Mg ²⁺	n/a.–336.0	48.6–465.2	n/a.–372.0
Br ⁻ , mg/dm ³	15.7–56.5	23.7–66.0	15.6–84.0
I ⁻ , mg/dm ³	0.8–23.3	0.8–22.7	2.1–26.5
Iron, mg/dm ³	0.4–16.7	0.2–47.0	0.2–49.0
Mineralization, g/dm ³	14.1–21.8	15.0–25.3	14.1–22.8
Hydrogen index, pH	5.6–8.3	5.5–7.9	5.5–8.5
Water density, g/cm ³	1.004–1.009	1.010–1.020	1.006–1.018
Water types, according to V.A. Sulin	Calcium chloride		
rNa/rCl metamorphosis coefficient	0.82–0.99	0.75–0.93	0.80–0.97
Number of samples studied (wells)	236 (20)	183 (12)	715 (4)

3. Methods

3.1. Analysis of geological structure and filtration-capacity properties of AAC AC rocks within the boundaries of the studied fields

The geological structure and rock composition of the AAC AC were assessed in

terms of compliance with the requirements for absorption horizons according to the regulatory documents. In general terms, they can be summarized as follows:

1. Groundwater of the absorption horizon, both at the time of its selection and in the foreseeable future, in the area of the sewage disposal site shall not be used for

domestic, drinking, medical, and industrial purposes, nor for heat and power supply.

2. The absorption horizon must be reliably isolated from the above- and below-ground horizons whose groundwater is used or is expected to be used in the national economy. Its isolating aquifers must be practically impermeable to wastewater and not be destroyed by it.
3. The absorbing horizon should have a high capacity, filtration, and favorable physical and chemical properties. The injectivity should not be significantly reduced due to the interaction of injected effluent with the rocks and groundwater of the horizon.
4. The depth of the absorption horizon should be as shallow as possible to minimize the cost of construction and operation of landfills.
5. The complexity and volume of exploration work required to justify the selection of the absorbing horizon should also be acceptable in technical and economic terms.

3.2. Systematization and collection of data on volumes of AAC AC water withdrawal for RPM and volumes of produced water surplus utilization in the AAC AC

According to the data of subsoil users of the Zapadno-Ust-Balykskoye, Megionskoye, and Taylakovskoye fields, the following parameters of RPM system functioning during oil production were estimated:

- volume of groundwater extraction of the AAC AC, thousand m³;
- accumulated volume of groundwater extraction of the AAC AC, thousand m³;
- volume of AAC AC produced water surplus disposal, thousand m³;
- accumulated volume of AAC AC produced water surplus disposal, thousand m³.

The growth of these parameters over time was plotted in parameter-time plots. The indicated extraction and disposal volumes were compared with the total values for Shirotnoye Priobie.

3.3. Analysis changes in groundwater quality indicators of the AAC AC according to the results of long-term monitoring

The array of data characterizing the groundwater quality indicators of reservoir waters of the AAC AC for the specified fields (macro- and micro components) in stage 1 was summarized in the table (Table 1). The data of chemical analyses characterizing the water quality after the RPM system application start (including the period of produced water surplus injection) (stage 2) were systematized in a similar form (Table 2).

Based on the systematized data, maps of hydrogeochemical conditions of reservoir waters of the complex were constructed for the main macro- and micro components (mineralization, Cl⁻, Ca²⁺, HCO₃⁻, I⁻, Br⁻) using the GST software package (Kurchikov et al., 2020) based on the generalized spline approximation method.

For the present studies, we used the entire available array of conditioned samples.

In order to visualise the presence of water quality transformation of AAC AC by the studied water quality components, hydrogeochemical maps were constructed in pairs, for two selected stages.

Also, the information on concentrations of the main indicators of groundwater chemical composition was drawn up in the form of histograms, making it possible to assess the presence of jumps of composition components relative to the original natural water quality of the AAC AC. Separately, plots of changes in the parameters of mineralization and total hardness of AAC AC groundwater during the whole period of field operation were constructed.

4. Results and Discussion

4.1. Analysis of the geological structure and filtration-capacity properties of AAC AC rocks within the boundaries of the studied fields

The geological structure and filtration-capacity properties of the AAC AC within the three fields under consideration were considered based on compliance with the requirements (Section 3.1) for absorbing horizons and horizons targeted for RPM water extraction.

Based on the material presented in 3.1, the following conclusions can be drawn:

1. Groundwater of the AAC AC is not planned for domestic use, drinking (due to high mineralization), therapeutic and industrial purposes, or heat and power supply. The AAC AC within the studied fields is not productive for oil and gas; therefore, water withdrawal or produced water injection cannot negatively impact hydrocarbon deposits.
2. The AAC AC is isolated from the horizons of the Cenozoic basin containing drinking water by a silty-clay aquifer (K2t-d) up to 770 m

thick. The AAC AC is also separated from the underlying oil-productive horizons by a complex of water-retaining rocks up to 250 m thick (K1br+K1b). Thus, the drinking water resources strategically crucial for the regional economy and hydrocarbon deposits (due to their absence in the AAC AC) will not be affected by water withdrawal and produced water injection into the AAC AC.

3. According to hydrodynamic studies, the AAC AC has high filtration-capacity properties: porosity from 26.1 to 29.4% and permeability of 0.163–0.530 μm^2 . Also, significant effective thickness (up to 370 m), high heads, and water availability of rocks determine its priority for use both as an absorbing horizon and a horizon targeted for water withdrawal for RPM.

Close genesis, the water quality of reservoir waters and injected produced water (Table 1, Table 3), as well as mineralogical composition with a predominance of quartz, absorbing horizon in the first approximation allows predicting the preservation of injectivity of the AAC AC.

Table 3. Water quality parameters of the produced water injected

Parameter name	Zapadno-Ust-Balykskoye field (2011–2023)	Megionskoye field (1967–2023)	Taylakovskoye field (2011–2023)
Anions, mg/dm ³			
HCO ₃ ⁻	85.0–5,980.0	54.9–1,403.5	183.0–21,96.7
Cl ⁻	5,318.0–25,170.0	7,444.0–17,725.0	7,090.0–18,904.0
CO ₃ ²⁻	n/a.–120.0	n/a.–24.0	n/a.–120.0
SO ₄ ²⁻	n/a	n/a.–78.0	n/a.–11.0
Cations, mg/dm ³			
Na ⁺ +K ⁺	3,371.8–17,369.6	2,460.0–10,616.8	4,613.8–10,902.0
Ca ²⁺	40.0–741.0	120.0–2965.9	85.1–1,684.0
Mg ²⁺	12.0–279.0	n/a.–535.0	n/a.–401.2
Br, mg/dm ³	–	41.0–55.3	–
mg/dm ³	–	2.1–14.8	10.4
Iron, mg/dm ³	1.19–22.58	0.9–28.0	0.5–37.2
Mineralization, g/dm ³	10.5–46.0	12.2–29.4	13.5–31.8
Hydrogen index, pH	5.5–8.2	5.6–8.1	6.0–8.4
Water density, g/cm ³	1.003–1.015	1.007–1.020	1.010–1.023

Table 3. Water quality parameters of the produced water injected (continued)

Parameter name	Zapadno-Ust-Balykskoye field (2011–2023)	Megionskoye field (1967–2023)	Taylakovskoye field (2011–2023)
Water types, according to V.A. Sulin	CC, MC, SHC	CC	CC, MC, SHC
rNa/rCl metamorphosis coefficient	0.87–1.34	0.53–0.97	0.79–1.05
Number of samples studied (wells)	85 (6)	221 (23)	121 (44)

Note. Water type according to V.A. Sulin: CC – calcium chloride; MC – magnesium chloride; SHC – sodium hydrocarbonate

It should be considered that in each case of justification of water selection for RPM or injection, it is necessary to carry out calculations on sedimentation modeling, taking into account individual reservoir water conditions (pressure and temperature), as well as chemical compositions of the mixed waters (Glebova & Lider, 2020; Rizzo et al., 2023; McMahon et al., 2023). Appropriate water treatment measures shall be designed if necessary and if any injection water quality requirements are not met

4.2. Systematization and collection of data on volumes of AAC AC water withdrawal for RPM, and on volumes of produced water surplus utilization in the AAC AC

Data on groundwater extraction volumes of the AAC AC, as well as placement of surplus produced water in the complex (including accumulated volumes) for the Zapadno-Ust-Balykskoye, Megionskoye, and Taylakovskoye fields are given in Section 2.2.

The accumulated volume of water extraction from the studied fields for the period of field operation at the end of 2023 varies from 14,709 thousand m³ to 55,189.4 thousand m³, and the accumulated volume of placement – from 4,516.7 thousand m³ to 16,152 thousand m³. These indicators are directly related to the length of field life, development regime, and water cut.

As noted in Skorobogatov et al. (2018) “Estimation of free gas potential resources in the Russian sedimentary basins...” the volume of sedimentary cover rocks of the West

Siberian megabasin (more than 11.5-12.0 million km³) and in general its scale provides conditions for the formation (and preservation) of very significant reserves of free gas and oil deposits. The scale of the basin also determines the availability of groundwater resources in the Mesozoic basin, which is many times higher than the demand for water for RPM. The above-mentioned values of water withdrawal and utilisation probably in real time practically do not influence the natural hydrodynamic situation, but at the same time the influence can be delayed in time.

4.3. Analysis of changes in groundwater quality parameters of the AAC AC according to the results of long-term monitoring

Modern water quality monitoring methodologies are improving and it has been repeatedly confirmed by studies should be based on a multi-factor approach and full real-time assessment of all possible risks (Fang et al., 2022; Li et al., 2017).

Davis et al. in a large-scale paper covering data from 487 US oil fields (2018) stress that regional groundwater monitoring should include the collection, analysis, and development of 3D visualizations of existing data, including geological structures, salinity mapping, identification of surface features that could potentially affect groundwater quality, location and depth of oil/gas and water wells, the cataloging of well construction, integrity issues and assessment of groundwater flow directions. Stephens et

al. (2021) clearly demonstrated that when studying changes in formation water quality as influenced by development and operational processes, variability in quality indicators such as dissolved solids content is largely controlled by stratigraphy and geological structure (e.g., area density of faults), but that increases in solids content are intensified by anthropogenic impacts on the reservoir.

When comparing the data presented in Table 1 and Table 2 on the water quality of AAC AC reservoir waters before the start of the RPM system and from the start of the RPM system until 2023, it can be concluded that there are no significant differences.

Figures 9-11 present maps showing water quality parameters such as: mineralisation, concentrations of chloride ions, calcium ions, calcium ions, hydrogen carbonate ions, iodine, and bromine for 2 stages before the RPM system was applied (Figures 3a, 3c, 4a,

4c, 5a, 5c) – Stage 1 and from the beginning of application (including produced water injection) to the present (Figures 3b, 3d, 4b, 4d, 5b, 5d) – Stage 2. Data from the studied fields and neighboring fields were used to construct the maps to show isolines of the component content in the regional plan. The spatial distribution of each of the listed parameters water quality of AAC AC chemical composition and its change from stage 1 to stage 2 is not significant. The distribution indicates the stability of the chemical composition despite the significant volumes of anthropogenic impact described in Sections 2.2 and 2.3.

Figure 12 presents histograms of changes in concentrations of main salt-forming ions, average values of mineralisation and plots of changes in total hardness in AAS VC waters for each of the three considered deposits.

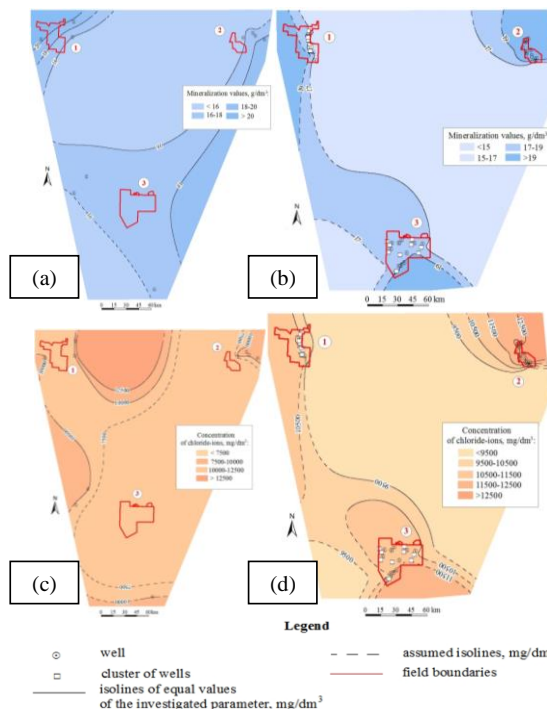


Figure 9. Hydrogeochemical maps of mineralization index and chloride ion concentration in AAC AC waters: (a), (c) – stage 1, (b), (d) – stage 2
Oil fields: 1 – Zapadno-Ust-Balykskoye, 2 – Megionskoye, 3 – Taylakovskoye

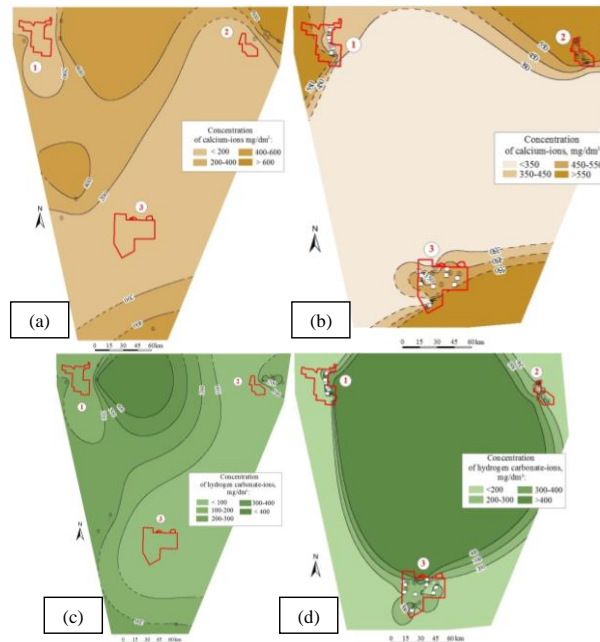


Figure 10. Hydrogeochemical maps of calcium ion and hydrogen carbonate ion concentrations in AAC AC waters: (a), (c) – stage 1, (b), (d) – stage 2. Symbols in Figure 9

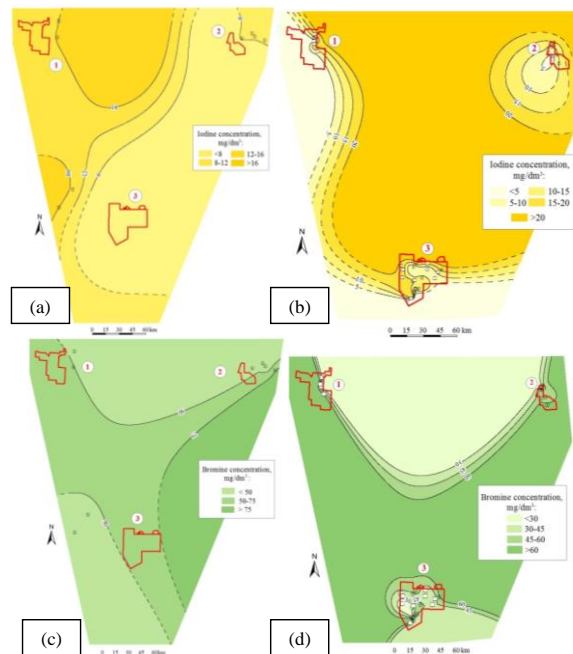


Figure 11. Hydrogeochemical maps of calcium and hydrogen carbonate-iodine ion and bromine concentrations in AAC AC waters: (a), (c) – stage 1, (b), (d) – stage 2. Symbols in Figure 9

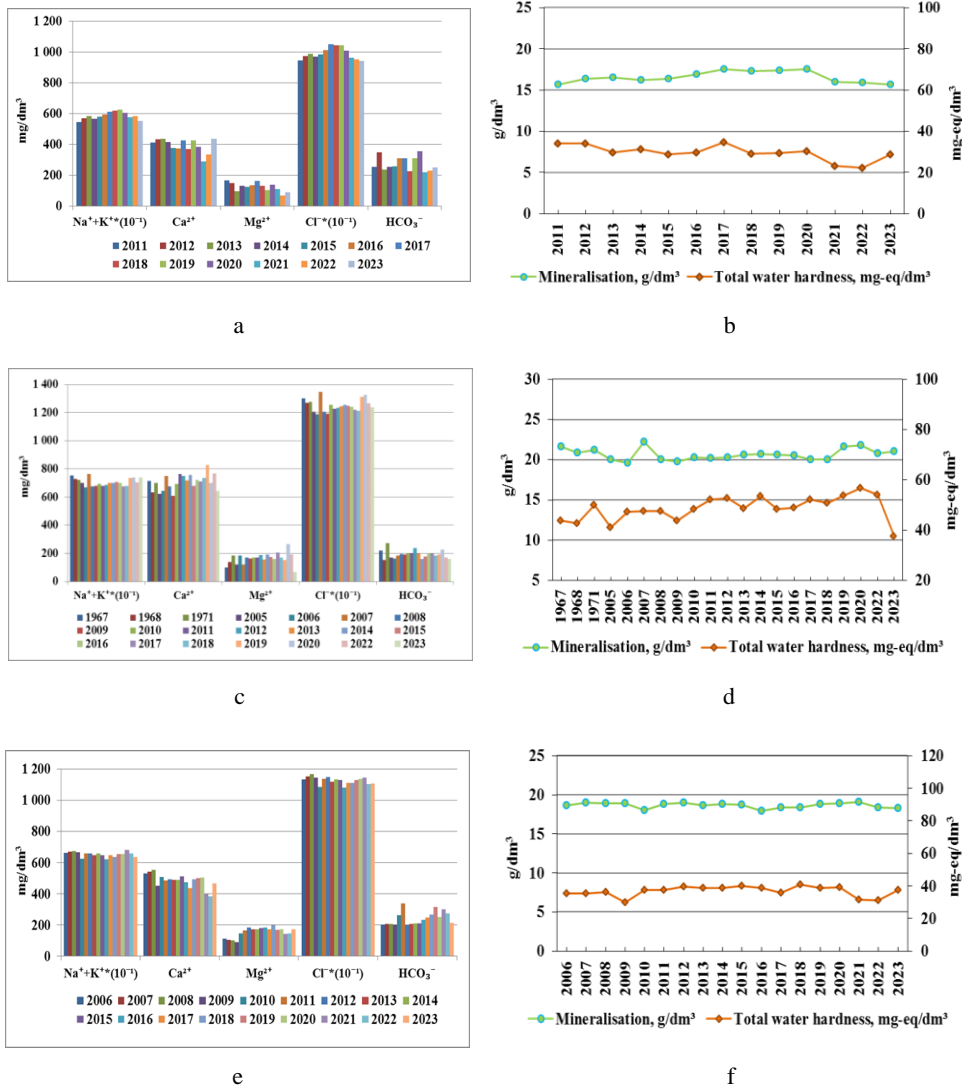


Figure 12. Histograms of changes in concentrations of groundwater quality indicators at the AAC AC. (a, b – Zapadno-Ust-Balykskoye field, c, d – Megionskoye field, e, f – Taylakovskoye field)

According to regime monitoring data (data from 236 samples were used for Zapadno-Ust-Balykskoye, more than 180 samples for Megionskoye, and more than 700 samples for Taylakovskoye), it is possible to draw a conclusion about preservation of water quality of AAC AC at the present time at the level characterising the beginning of technogenic impact. Water quality of the

AAC AC of the studied fields is characterised by preservation of the ratio of main salt-forming ions.

Some sporadic fluctuations of mineralization and total hardness values were recorded for the Megionskoye field. However, due to the long period of observations of water chemistry (56 years), the detected “jumps” are probably related to different laboratory

methods that were applied in one or another period.

5. Conclusion

The study confirmed the hypothesis that at the current time, the equilibrium reserve in the system “water-rock” of the AAC AC, as well as the volumes of impact, are leveled by the “natural” capacity of the AAC AC, the water quality of the complex is preserved:

1. The geological structure and filtration-capacity properties of AAC AC rocks and high water availability are favorable for using the complex both as an absorbing horizon and as a source for the withdrawal of large amounts of mineralized water for RPM operation.
2. Systematization and collection of data on AAC AC water withdrawal volumes for RPM and volumes of produced water surplus utilization in the AAC AC for Zapadno-Ust-Balykskoye, Megionskoye, and Taylakovskoye fields showed that there was a stable growth of water withdrawal and utilization. The situation is similar for a number of other hydrocarbon fields in Shirotnoye Priobie. These processes caused the redistribution of water in the Mesozoic hydrogeological basin, the extent of which scientists will have to estimate soon.
3. Analysis of changes in indicators of the chemical composition of groundwater of the AAC AC (mineralization, concentration of chorus ions, calcium ions, hydrocarbonate ions, iodine and bromine, and others) according to the results of long-term monitoring showed preservation of type identity and the water quality of the AAC AC waters due to close composition of injected water extracted with oil from productive horizons.

At present, we observe a relative stability in the quality of AAC AC, but it should be realised that this stability may be temporary, approaches to groundwater monitoring in hydrocarbon fields should be improved (Jia et al., 2022), and transparency and accessibility of data and analyses of groundwater monitoring in hydrocarbon fields should be maintained (McMahon et al., 2023; Li et al., 2017). Hydrogeochemical maps of deep horizon groundwater conditions reflect the real environmental situation when constructed with an optimal amount of information and taking into account natural and anthropogenic hydrodynamics (Fetter, 2001; Tóth, 2009; Wasteby et al., 2014).

The groundwater status of the AAC AC, as a complex subject to a variety of anthropogenic impacts, should be kept under constant close monitoring and new control methods, which are practically not applied at present, should be introduced. These primarily include performing isotopic (McMahon et al., 2023; Besser et al., 2019; Wright et al., 2019; Birkle et al., 2006) and microbial community composition analyses (Youssef et al., 2009; Semenova et al., 2020; Zhong et al., 2020). Understanding where the areas of risk and impacts are, and responding with effective water quality management strategies, is integral to responsible and efficient operations in the oil and gas sector (Ergun et al., 2014). This is an essential condition for the environmental safety of oil and gas industry operations to preserve the natural water quality of the AAC AC of Western Siberia.

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Rimma Abdrashitova

Industrial University of
Tyumen,
Tyumen,
Russia
abdrashitovarn@tyuiu.ru
ORCID 0000-0002-7060-0701

Yulia Salmnikova

Industrial University of
Tyumen,
Tyumen,
Russia
salmnikovaji@tyuiu.ru
ORCID 0000-0001-7864-9115

Andrey Plavnik

West Siberian Division of
Trofimuk Institute of
Petroleum-Gas Geology and
Geophysics of the Siberian
Branch of the RAS,
Tyumen,
Russia
plavnikag@tyuiu.ru
ORCID 0000-0001-8099-4874

Yulia Sretenskaya

Industrial University of
Tyumen,
Tyumen,
Russia
sretenskaiajf@mail.ru
ORCID 0009-0009-4681-5620

Xiaopu Wang

State Key Laboratory of Deep
Oil and Gas, China University
of Petroleum (East China),
Qingdao, Shandong,
China
wxp@upc.edu.cn
ORCID 0000-0003-1013-2691

Victoria Kolotygina

University of Tyumen,
Tyumen,
Russia
mns@vkolotygina.ru
ORCID 0000-0001-6368-4815

Mikhail Poluyanov

Federal State Budgetary
Institution “State Commission
on Mineral Reserves”,
Russia
poluyanov@gkz-rf.ru
ORCID 0009-0003-6380-2422
