

RESEARCH ARTICLE

REGULATORY FRAMEWORK FOR PRODUCED WATER MANAGEMENT AT THE KAMENNY SUBSURFACE PETROLEUM SITE IN WEST SIBERIA

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ARTICLE DETAILS

Article History:

Received 25 September 2022
Revised 29 October 2022
Accepted 04 November 2022
Available online 09 November 2022

ABSTRACT

The present study aimed to assess the safety in use of the Aptian-Albian-Cenomanian aquifer system within the Kamenny subsurface site, located in the West-Siberian petroleum region of Russia, when the produced waters resulting abundantly from oil extraction are injected thereto. The relevance of this study is necessitated by the need to dispose of produced waters (co-extracted with oil) within the Kamenny site, whose accumulated volume is currently estimated to be over 10,000 thousand m³. That said, the most important challenge facing the subsurface users is to minimize the adverse impact on the geological environment by water injection into the lost-circulation horizon and preserve the natural balance of the geological environment. This study has addressed the following problems: the natural geological-hydrogeological conditions of the Aptian-Albian-Cenomanian aquifer complex were assessed; the stability of hydrogeochemical measures of groundwaters was analyzed from the monitoring survey results (starting from the 1960s); the compatibility between the produced and reservoir waters was evaluated by estimating the carbonate balance of the system; and the stability of hydrogeochemical measures of the Atlym-Novomikhailovsk aquifer complex that holds fresh potable waters valuable for the drinking and domestic water supplies and overlies the Aptian-Albian-Cenomanian aquifer system. The solution found for each of the above-listed problems evidences the consistency of the hypothesis suggested herein that the Aptian-Albian-Cenomanian aquifer system is currently safe to use for the purpose of produced water (co-extracted with oil) injection. This paper also places emphasis on the necessity of continually improving the monitoring system for both the lost-circulation horizon and the overlying ones, and of scrupulously complying with all of the environmental safeguards, which is a mandatory prerequisite for retaining the natural balance of the subsurface resources of the West-Siberian petroleum region in Russia.

KEYWORDS

petroleum hydrogeology, reservoir pressure maintenance (RPM), carbonate balance, groundwater salinity, reservoir temperature, produced water

1. INTRODUCTION

The accumulated volume of groundwaters that are co-extracted with oil has reached 7.4 billion cubic meters in over a half-century (55 years) since the development of major West-Siberian hydrocarbon fields, while the fields with an organized reservoir pressure maintenance (RPM) system that is based on the Aptian-Albian-Cenomanian water have exceeded 330 in number. The produced water injection into the Aptian-Albian-Cenomanian deposits as the type of subsurface use has increasingly been gaining a wider use in West Siberia over the last 20 years. This is associated with an increased water-cut of the extracted oil, creating a surplus in the produced water whose volumes exceed the RPM system's demand for water manifold (Matusevich, 1999; Pavlyukov et al., 2021). One hundred and sixty six injection stations for the produced water surplus are currently operating on the West-Siberian terrain. For the year 2021, the total volume of the liquid injected into the Aptian-Albian-Cenomanian lost-circulation horizon accounted for 771 million m³, and chances are high that the injection volumes will only be growing in the future.

Therefore, the analysis of the geological-hydrogeological condition features of the specific field and of the parameters characteristic of the

produced-water injection demonstrates that the concerns of safety in use of the Aptian-Albian-Cenomanian aquifer system (AAC AS) are highly relevant for the preservation of the natural balance of subsurface resources. These concerns have been addressed in detail herein, as exemplified by the Kamenny subsurface site. The generalized data on exploitation regimes of the injection and fluid recovery sites within the survey area are depicted in Figs. 1 and 2. It is simply evident that the volumes of water injected into the horizon in order to enhance the oil recovery and of injected produced water surpluses are considerably growing.

The development of the field in question is run using a reservoir pressure maintenance (RPM) system in which fresh groundwaters of the Oligocene-quaternary sediments (the Atlym-Novomikhailovsk aquifer complex) are employed along with the produced water. The peculiarities of the oilfield infrastructure do not allow the entire volume of produced water to be engaged, therefore the water surplus occurs at separate sites. The injection of produced water and of waters used for one's own production and technology needs has been conducted since 2011 and is presently more than 10,000 thousand m³ in volume. Such volumes of the injected produced water undoubtedly require continuous monitoring and comprehensive observations (Abalakov, 2007; Ziling and Trofimov, 2002).

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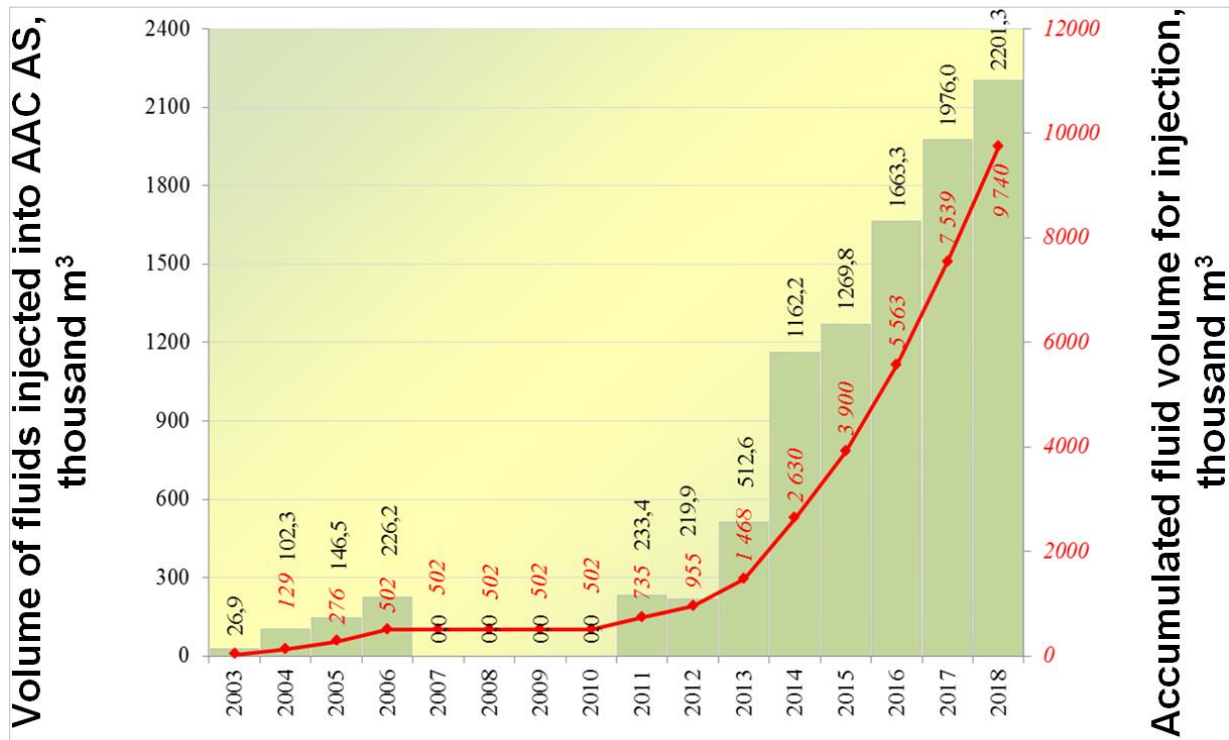


Figure 1: Time profile of the injection of produced water surplus into the Aptian-Albian-Cenomanian aquifer system (AAC AS) at the Kamenny subsurface site

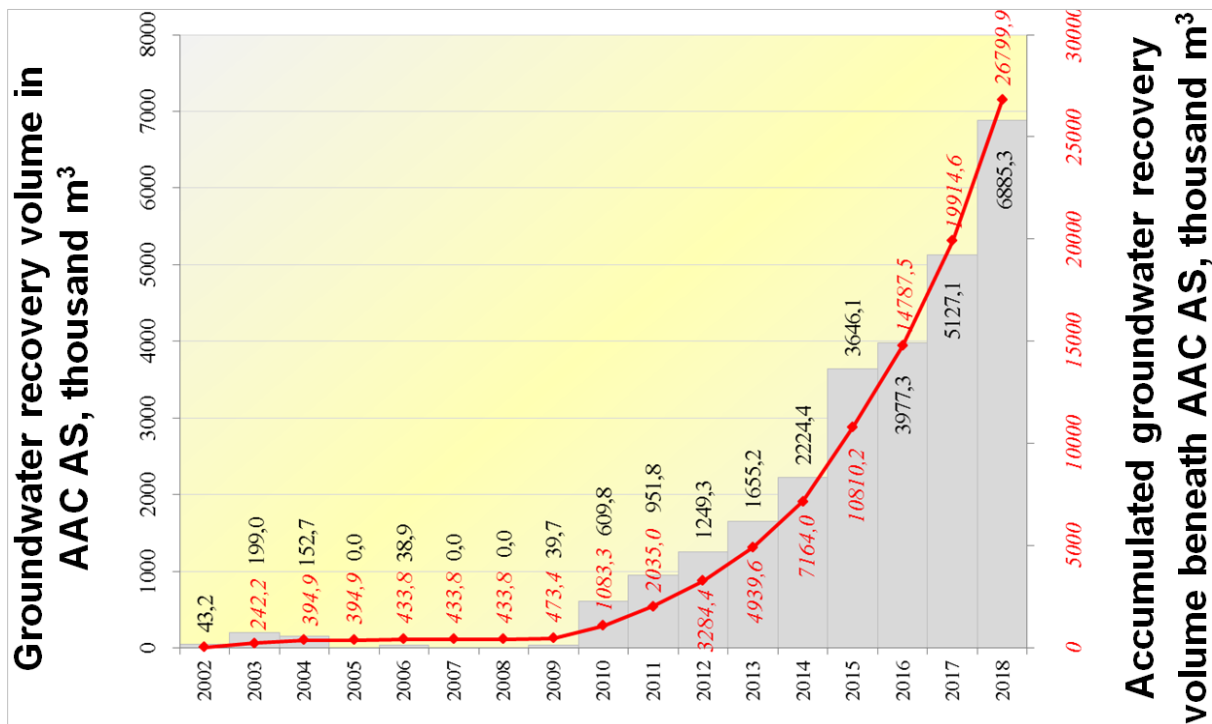


Figure 2: Time profile of the groundwater recovery in the Aptian-Albian-Cenomanian aquifer system (AAC AS) at the Kamenny subsurface site

To look into the issue of safety in use of the AAC AS for the purpose of produced water injection at the subsurface site under survey in West Siberia, the following problems should be addressed:

1. Evaluate the natural geological-hydrogeological conditions of the AAC AS within the Kamenny subsurface site;
2. Analyze the stability of hydrogeochemical measures of the AAC AS groundwaters from the monitoring study findings;
3. Assess the compatibility between the produced and reservoir waters injected into the AAC AS;
4. Evaluate the stability of hydrogeochemical measures of the Atlym-Novomikhailovsk aquifer complex that comprises drinking freshwaters and is located in the upper West-Siberian megabasin. The stability of the

hydrogeochemical setting of the said aquifer complex will be an evidence of no crossflows coming "from below" due to different reasons that are discussed hereinafter.

The hypothesis suggested herein holds that if the reported research problems have positive solutions, it can be stated that the AAC AS is presently safe to use for produced water injection at the Kamenny subsurface site in West Siberia.

The present study aimed to evaluate the safety in use of the Aptian-Albian-Cenomanian aquifer system (AAC AS) within the Kamenny subsurface site located in the West-Siberian petroleum region when produced waters originating in large amounts from oil production are injected thereto.

The aforesaid problems represent subsections in sections "Methods", "Results and discussion" of the present study.

2. MATERIALS

2.1 Features of Geological, Hydrogeological and Geotemperature Conditions at the Kamenny Subsurface Site

2.1.1 Geological and Hydrogeological Conditions

The Kamenny subsurface site is administratively located on the territory of the Khanty-Mansiysk and Oktyabr'skiy Districts of Khanty-Mansiysk Autonomous Okrug—Yugra, in Tyumen Oblast, Russia.

Three groundwater basins are discernible in the cross-section of the field, as in the entire West-Siberian megabasin (Nudner, 1970; Matusевич et al., 2005; Stavitskii et al., 2006): the Cenozoic, Mesozoic and Paleozoic (Fig. 3). The AAC AS holding a huge resource potential of mineralized groundwaters refers to the Mesozoic basin ($K_{1a2}+K_{2cm}$, K_{1a1} , K_{1ap}) and is the most arially and cross-sectionally persistent among the Mesozoic deposits of the sedimentary platform. In the survey area, this aquifer is confined to the deposits of the Uvat, Khanty-Mansiysk and Vikulov suites.

The Uvat and Vikulov suites are the reservoirs of the AAC AS. From a lithological point of view, the aquifer system is made up of a complex and non-uniform alternation of compacted sands, sandstones, aleurolites and clays, with the latter prevailing in the Lower Khanty-Mansiysk subsuite. The AAC AS reservoirs refer to classes I–III as per Khanin's classification (Khani, 1969), while their overlying strata, chiefly the clayey ones, refer to reliable aquicludes of classes I–III. The aquifer system within the survey area is about 800–900 m thick, and the burial depth of the AAC AS roof (the roof of the Uvat suite) varies from 956 to 1008 m within the field. The clay deposits of the Upper-Jurassic aquifer system, with a thickness of about 300 m, serve as an subjacent aquiclude.

The Mesozoic basin includes the bottom of the regional aquiclude (K_{2t-d}) which, together with Palaeocene and Eocene sediments (P_{1-2}), overlay the water-bearing portion of the AAC AS, thereby isolating the mineralized waters of the AAC AS and Lower-Jurassic aquifer system from freshwaters of the Cenozoic groundwater basin. The gross thickness of the said regional aquiclude made up of argillaceous-siliceous rocks is about 750 m.

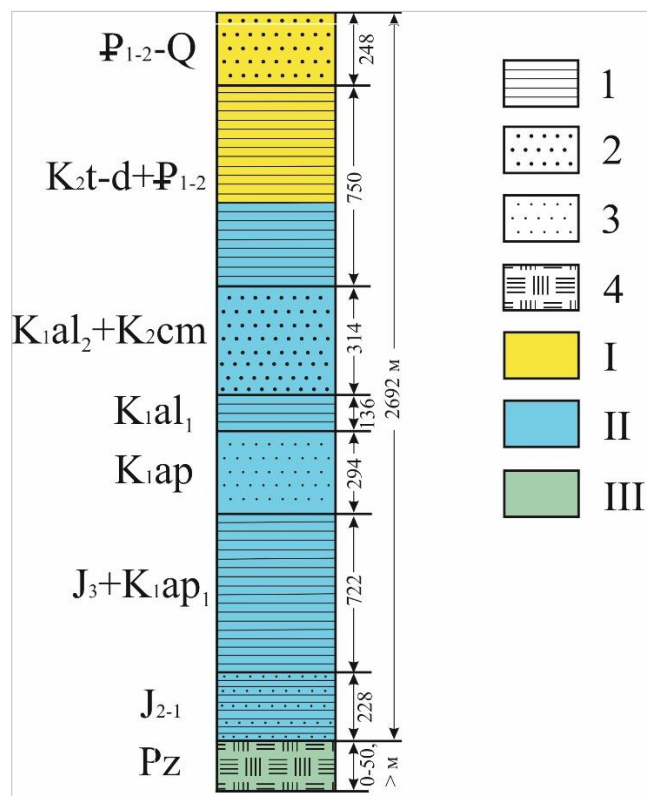


Figure 3: The conceptual geologic cross-section of the sedimentary platform at the Kamenny subsurface site. Symbols: 1. clay rocks, 2. coarse-grained sandstones, 3. fine-grained sandstones, and 4. tuffaceous sedimentary rocks. Groundwater basins of the West-Siberian megabasin: I. Cenozoic, II. Mesozoic, and III. Paleozoic

The chemical composition of the AAC AS reservoir groundwaters, i.e. of the Uvat and Vikulov suites, is given in Table 1.

The waters contained in the Uvat and Vikulov sediments are sodium chloride in terms of chemical composition; the type of water contained in the Uvat suite is calcium chloride (as per Prof. Sulin's classification) and that contained in the Vikulov suite is sodium bicarbonate. The salinities of the reservoir waters within both suites are almost similar, 12.4 mg/dm³ for the Uvat suite and 11.6 mg/dm³ for the Vikulov suite on average. The brine-ionic composition contains chiefly sodium and chlorine ions and less calcium, magnesium and bicarbonate. The total hardness of the groundwaters is 14.3 mg-eq./dm³ (the Uvat suite) and 11.6 mg-eq./dm³ (Vikulov suite) on average. In terms of hydrogen ion concentration index, the waters are mainly neutral and contain no sulfate ions. Overall, the Uvat suite waters are less metamorphized (the rNa/rCl varies from 0.93 to 0.99) than those of the Vikulov suite (the rNa/rCl is 1.00 to 1.09), satisfying the groundwater formation conditions during the Aptian and Cenomanian Ages (Abdrashitova, 2017).

The micro-elemental composition of the groundwaters of both suites is made up of iodine, bromine and iron. The contents of these micro-elements match the regional hydrogeochemical background of the AAC AS.

The water-dissolved gas has a methanoic composition. Hydrogen sulfide was not detected; the content of nitrogen is 2.21–5.75 vol.%, carbon

dioxide 0.06–0.65 vol.% and hydrogen 0.01–1.36 vol.%. In accord with the regional data, the operations area is situated in the zone of an unordered change in the groundwater gas-saturation within 1.0–1.5 m³/m³ (Kruglikov et al., 1985).

Overall, the composition and properties of the AAC AS reservoir waters fit with the background readings of this region and have no deviations (Abdrashitova and Kadyrov, 2022; Kurchikov and Playnik, 2016).

The aquifer horizon enclosed in the Uvat suite sediments ($K_{1a2}+K_{2cm}$) is the target lost-circulation horizon within the Kamenny subsurface site. Therefore, a further analysis will rely on data of this particular horizon. The Cenomanian deposits exhibit high porosity & permeability properties of rocks, as does the entire AAC AS, which is why they are used as the lost-circulation reservoir for disposal of produced waters (Beshentsev, 2018; Dyunin, 2000; Borovskaya et al., 2012). The area-wise distribution pattern of groundwater salinity of the subsurface site is rather quiet; a tendency is observed towards a decline in the values to the southeast part of the subsurface site (Fig. 4), which is attributed to lithological and paleogeographic conditions of the genesis of the AAC AS groundwaters.

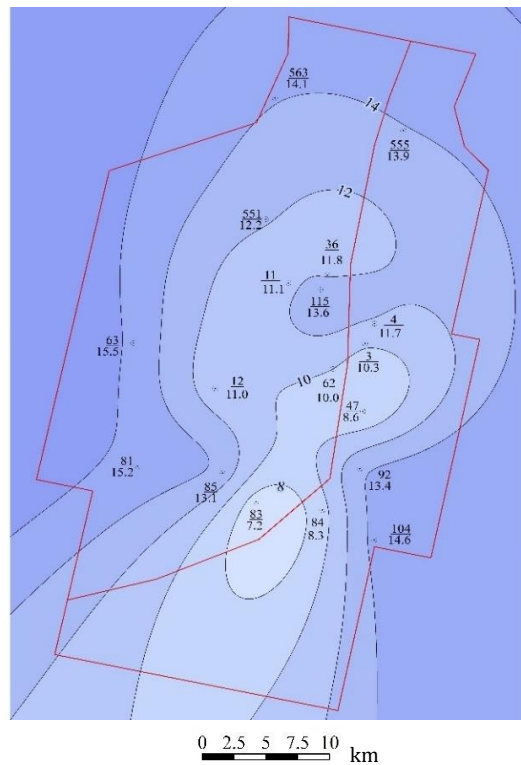
2.1.2 Tectonic and Geotemperature Conditions

From a tectonic point of view, the Kamenny subsurface site relates to the Kamenny local uplift which in turn is part of the Krasnoleninsky arch.

The arch is situated in the south-western West-Siberian petroleum province, being parted from the contiguous positive structures of the same order by the Elizarovsky mega-sag eastwardly and by the Mutomsky

trough westwardly; the arch is coupled with the Shaimsk megaswell by the Pottymsk mega-sag southwardly and by the Khanty-Mansiysk depression eastwardly.

Table 1: Basic Physicochemical Characteristics of the AAC AS Reservoir Waters at the Kamenny Subsurface Site				
Indicator	Uvat Suite		Vikulov Suite	
	Min.-Max.	Mean	Min.-Max.	Mean
<i>Macro-elements</i>				
Hydrogen ion concentration index (pH)	6.7-8.4	7.9	6.0-7.0	6.5
Specific weight, g/cm ³	1.006-1.008	1.007	no	no
Salinity, g/dm ³	11.0-14.7	12.4	7.2-15.5	11.6
Total hardness, mg-eq./dm ³	10.0-16.0	14.3	4.2-25.2	11.6
Sodium+potassium Na ⁺ +K ⁺ , mg/dm ³	3989.0-5640.0	4540.7	2549.0-5755.1	4136.9
Magnesium Mg ²⁺ , mg/dm ³	36.0-62.0	51.1	14.4-80.4	43.5
Calcium Ca ²⁺ , mg/dm ³	140.0-240.0	200.9	60.0-244.0	159.5
Chlorides Cl ⁻ , mg/dm ³	6383.0-8339.0	7167.2	3624.6-8672.7	6174.3
Sulfates SO ₄ ²⁻ , mg/dm ³	0.2-1.5	0.76	no-1.2	1.1
Bicarbonates HCO ₃ ⁻ , mg/dm ³	232.0-732.0	423.0	693.0-1411.2	1058.4
Carbonates CO ₃ ²⁻ , mg/dm ³	no-2.0	2.0	no-no	no
<i>Micro-elements</i>				
iodine I, mg/dm ³	8.9-10.6	9.8	6.1-14.9	11.6
Bromine Br, mg/dm ³	7.0-35.4	25.9	25.3-45.6	35.0
Boron B, mg/dm ³	no-no	no	6.1-20.2	11.7
Iron Fe ²⁺ , mg/dm ³	5.8-11.5	8.2	0.5-2.0	1.25



Symbols:	
	Well from which water samples were collected. The numerator is the well ID no., and the denominator is the salinity expressed in g/dm ³
Groundwater salinity values, g/dm ³ :	
	<8
	8-10
	10-12
	12-14
	>14

Figure 4: A schematic map of the groundwater salinity distribution of the Cenomanian horizon of the AAC AS.

Note to Fig. 4: the coordinates of the most northerly points of the site correspond to (from the right to the left): No.1 61°45'00"N, 67°15'00"E; No.2 61°45'00"N, 67°3'00"E. The coordinates of the most southerly points of the site correspond to (from the right to the left): No.3 61°09'00"N, 67°36'00"E; No.4 61°09'00"N, 67°06'00"E

The basement framework of the sedimentary platform within the subsurface site in question characteristically exhibits numerous intrusions and disjunctive faults (Matusevich et al., 2013; Toth, 2009). We previously reported how such a basement framework affects the hydrogeological conditions of the Jurassic sediments being laid down directly in the basement. The disjunctive faults extending across the entire strata of the Jurassic deposits can serve as channels of crossflows between beds, which governs the hydrogeologic field contrast. These crossflows are not typical of the AAC AS because a thick regional aquiclude is present between the Jurassic and Aptian-Albian-Cenomanian deposits (Fig. 3), reliably isolating the bottom of the Mesozoic groundwater basin from its top and being a kind of a "barrier" to the growth of disjunctive faults spreading from the basement.

The Krasnoleninsky petroleum district whose eastern part encompasses the Kamenny subsurface site is a unique region (along with the Salym district in West Siberia) wherein a large high-amplitude geothermal anomaly embracing most of the Kamenny site is clearly defined. The anomaly manifests itself in lateral temperature drops to +20°C and more at relatively small areas. It is the most pronounced in the Bazhenov (Tutleymask) suite located inferior to the AAC AS. The lateral temperature amplitude diminishes upsection (Kurchikov et al., 1987). The estimated heat flow here attains 80.0 mW/m² and more, and the values are minimal and about 60.0 mW/m² only in the western part (within the Kalmanovsky small sag). Overall, the geothermal gradient variations are attributed to the rock lithology; however, certain variations are due to the geotemperature field history in this area.

The leading causes of the existent geotemperature anomaly are the ingress of heat through the basement faults and the expulsion of waters from the

Bazhenov (Tutleymask) suite, the latter probably being a decisive factor.

The temperature distribution across the sedimentary platform section, as acquired by the procedure developed by the West-Siberian Research Institute of Geology and Geophysics, clearly correlates with the thermal field features. According to the results from spot measurements of temperatures (archive materials) performed while testing the exploratory wells at the Kamenny area, the rock temperature of the Vikulov suite varies from +56 to +77°C, and the rock temperatures in the roof of the Uvat suite (the Cenomanian roof) are about +36 to +52°C, elevating West-to-East. The temperature of the Jurassic and pre-Jurassic rocks ranges from +80 to +130°C. The variation patterns are completely governed by the variation patterns of deep heat flow noted above.

2.2 Characterization of Injected Produced Water

At present, the waters injected on the territory of the Kamenny subsurface site represent a blend of co-extracted reservoir waters originating from the development of oil-productive deposits from the Cretaceous (beds VK₁, VK₂₋₃), Jura (BG, JK₂₋₉, JK₁, JK₀) and weathering crust. The chemical composition and quality of these waters are dependent on physicochemical characteristics of produced (co-extracted) waters and on their ratio in the blend.

The water content of the well products is 52–55% at the Kamenny subsurface site (as per the subsurface user's data). It is clear at this point that a further oil production will be accompanied by an increase in water-cut. The era of "easy" oil is ending, and the geologists are faced with even more complicated and complex problems (Hughes and Rudolph, 2011).

The chemical composition of the injected waters at the Kamenny subsurface site has been examined from the results of 24 control samples that have been collected during the exploitation of absorbing wells (since 2011) and to present, which allowed the evaluation of background readings of basic indicators of the chemical composition of waters (Table 2).

Table 2: Basic Physicochemical Characteristics of Produced Water at the Kamenny Subsurface Site

Indicators	Study period of Time	
	Before 2011, 16 samples	To present, 8 samples
hydrogen ion concentration index pH, pH units	6.8–7.3	6.6–8.0
Specific weight, g/cm ³	1.005–1.015	1.001–1.013
Calcd. salinity, g/dm ³	9.5–17.9	9.4–19.2
Total hardness, mg-eq./dm ³	5.5–17.8	13.1–21.2
Na ⁺ , mg/dm ³	3433–6500	3050–6940
K ⁺ , mg/dm ³	40–70	60–100
Mg ²⁺ , mg/dm ³	28–125	43–122
Ca ²⁺ , mg/dm ³	51–210	180–224
Cl ⁻ , mg/dm ³	4935–9929	4964–10638
SO ₄ ²⁻ , mg/dm ³	abs.	abs.
Bicarbonates HCO ₃ ⁻ , mg/dm ³	830–1191	952–1251
Carbonates mg/dm ³	abs.	abs.
Iron, mg/dm ³	N/A	5.4–15.0

The produced water is almost similar in its chemical composition and properties to reservoir waters of oil-productive deposits. The waters have a sodium chloride composition and are a sodium bicarbonate or calcium chloride type (as per Prof. Sulin's classification), with a salinity of 9.4–19.2 g/dm³, and their brine-ionic composition contains chiefly sodium and chlorine ions and less calcium, magnesium and bicarbonate ions, as do the waters of the Cenomanian lost-circulation horizon. The total hardness is 5.5–21.2 mg-eq./dm³; in terms of hydrogen ion concentration index, the waters are basically neutral, more rarely weak-alkaline with pH=6.6–8.0, and contain no sulfate ions.

2.3 Geologic-Hydrogeological Features of the Atlym-Novomikhailovsk Aquifer Complex Containing Fresh Groundwaters

Here, we take a look at the Atlym-Novomikhailovsk aquifer complex containing fresh groundwaters in view of the fact that it overlies the target lost-circulation horizon, and the injection of produced water (co-extracted with oil) may theoretically have an adverse impact on the stability of the hydrogeochemical conditions of this aquifer complex. The reasons behind

it can be crossflows and intrusions of process fluids into the aquifer complex through the borehole annulus and of injected mineralized water, as well as contamination of the aquifer complex from above in the case of any failures in operation of injection sites (Bespalova, 2015; Bespalova, 2015; Bespalova, 2016; Fetter, 2001).

The aquifer complex in question refers to the Atlym and Novomikhailovsk suites of the Paleogene System of the Cenozoic basin. The total thickness of the aquifer complex is up to 100 m, and the depth of burial is 60 to 160 m. The rocks are composed of inequigranular quartz-feldspar sands, with alternating grey and brown clays and aleurolites; coal seams are sometimes found.

The Atlym-Novomikhailovsk aquifer waters at the site under study are mainly bicarbonate and have a variable cationic composition, with a salinity of 0.300–0.531 g/dm³; the dry residue value is 195.0–358.0 mg/dm³. In terms of hydrogen ion concentration index, the waters range from weak-alkaline to alkaline (pH=6.0–8.8), from moderately hard to hard (as per Prof. Alekin), and the total hardness is 3.5–6.4 mg-eq./dm³.

The Atlym-Novomikhailovsk aquifer system is a major target object for drinking, domestic and process water supplies for the entire West-Siberian region. The aquifer system holds huge reserves of fresh groundwaters that meet the sanitary-hygienic requirements by most indicators. The most common exception is the contents of iron, manganese and silicon, and organoleptic indicators such as colority and turbidity, ensuing from the natural hydrogeochemical features of the Paleogene System of the West-Siberian megabasin.

3. THEORETICAL BASICS

3.1 Requirements for Geologic-Hydrogeological Characteristics of Lost-Circulation Horizon

The maintenance of exploitation of almost any oilfield and related concomitant processes such as produced water injection is a sophisticated and interdisciplinary challenge. Comprehensive characterization of a reservoir, with geologic and hydrogeological conditions thoroughly taken into account, is considered to be prerequisite to accurate evaluation of porous medium properties that have a direct impact on flow characteristics (Druetta et al., 2016; Meite et al., 2022; Bear, 1972; Dahlberg, 1982; Kreitler, 1989; Tissot et al., 1984; Toth, 1999; Maliva, 2016).

In accord with the normative documentation requirements, it is believed from the standpoint of geologic-hydrogeological condition analysis that groundwaters of a lost-circulation horizon, both at the time the horizon is chosen and in the foreseeable future, should not be used for drinking and household purposes, therapeutic and industrial purposes, nor for heat- and power supply in the area of produced water injection. The water injection also must not adversely affect gas and oil deposits confined to the horizon. The lost-circulation horizon must reliably be isolated from overlying and underlying horizons whose groundwaters are in use or expected to be used in the national economy. The aquicludes isolating the horizon must be nearly impermeable to the injected waters and must not be destroyable when exposed to the latter. The lost-circulation horizon must have high porosity & permeability properties and favorable physicochemical properties to ensure the required horizon injectivity index at acceptable injection pressures from a technico-economical perspective. In addition, the injectivity index must not decline considerably as the injected wastewaters interact with rocks and horizon waters. Here, we mentioned only the essential requirements for the lost-circulation horizon. More details can be found in published papers (Mashorin and Fominykh, 2013; Mashorin et al., 2014; Salnikova and Radchenko, 2011; Delia et al., 2013) and normative documentation used by the subsurface users. The anthropogenic transformation by water injection is often associated with a decline in elastic properties of productive and water-bearing beds. Apart from fluid-flow processes, a significant effect is exerted by capillary pressures confined to productive beds being under anthropogenic exposure (RPM system, injection of produced water surplus, etc.) (Kovyatkina and Matushevich, 2015; Matushevich and Kovyatkina, 1997; Matushevich and Semenova, 2009). Therefore, it is important to monitor these parameters when choosing and using a lost-circulation horizon.

3.2 Quality Assessment of Injected Fluids

A normative document regulating the quality of fluids injected into a lost-circulation horizon is currently lacking. Given that the requirements for injected water quality reduce to normalizing those indicators that govern the impairment of fluid-flow properties of a reservoir, the industry standard No. 39-225-88 "Water for Waterflooding of Oil Reservoirs. Quality Requirements" can be adopted as the normative document, which has been in use by the subsurface users in the West-Siberian petroleum region for decades.

The quality attributes such as hydrogen ion concentration index, dissolved oxygen content, concentrations of hydrogen sulfide, iron (III) ions, mechanical impurities and petrochemicals, as well as water aggressivity and swelling ability of reservoir argillaceous minerals are regulated for injected waters.

The industry standard's basic requirement is to control fluid-flow properties of reservoirs and well injectivity index whose decrement is permissible by no more than 20% from the beginning of injection. Otherwise, appropriate measures for water conditioning should be taken, with the standard's requirements taken into account. The relative error of the technique is 15%. Different factors may cause the well injectivity to decrease. For instance, the co-presence of hydrogen sulfide and iron (III) ions in water under certain conditions may bring about iron sulfide, an insoluble salt, and hence increase the content of mechanical impurities in

injected waters. The ingress of injected waters into the lost-circulation horizon may cause the swelling ability of reservoir clay minerals to rise. The swelling degree depends on the salinity of injected water and increases as the salinity declines. No swelling is foreseeable when injecting waters whose salinity is lower than that of the lost-circulation horizon if the content of divalent cations (Mg^{2+} и Ca^{2+}) with respect to total cations of injected waters is higher than that of the lost-circulation horizon waters (Kashchavtsev et al., 1985; Kashchavtsev, 2000). When addressing the issues of injecting waters with a salinity higher than that of reservoir waters for the RPM purpose, there arise similar problems whose developed solutions can also be applied to the injection of produced water surplus (Khishvand et al., 2019; Mungan, 1965; Bertero et al., 1988).

The waters (the reservoir and injected ones) miscible under reservoir conditions are considered compatible if the amount of sediment resulted from their mixing does not exceed the values set forth in the industry standard No. 39-225-88, with the reservoir properties of the lost-circulation horizon taken into account; otherwise, appropriate measures for water conditioning should be taken, given the standard's requirements. Many authors note the need for an accurate simulation of the behavior of injected solutions in the reservoir both for the injected water-reservoir water interaction and for the mixed reservoir/injected waters-reservoir rock surface interaction (Gerritsen et al., 2005; Patel et al., 2019; Scardovelli and Zalewski, 1999; Su et al., 2018; Demir, I. 1995).

It is also mandatory to monitor the macro-elemental composition of produced water once conditioned for injection Abukova et al., 2013; Abukova et al., 2015; Abukova et al., 2012; Delia et al., 2012).

4. RESEARCH METHODS

4.1 Evaluation of Natural Geologic-Hydrogeological Conditions of the AAC AS Within the Kamenny Subsurface Site

The evaluation of the natural geologic-hydrogeological conditions was performed to analyze how the Cenomanian deposits that are a lost-circulation horizon in the Uvat suite comply with the normative documentation requirements for selecting a lost-circulation horizon, as briefly set forth in sub. 3.1. To evaluate the porosity & permeability properties, the results from geophysical surveys and interference testing of wells performed within the Kamenny subsurface site were employed herein.

4.2 Stability Evaluation of Hydrogeochemical Measures of the AAC AS Groundwaters by Monitoring Survey Results

Here, we employed the results from chemical assay of the lost-circulation horizon from 1960 to 2015–2017 to evaluate if hydrogeochemical indicators of the AAC AS groundwaters are stable. Documenting the changes in groundwater salinity, concentrations of major macro-elements and micro-elements, and hydrogen ion concentration index and specific weight of groundwaters allows one to judge if there is a transformation of the hydrogeochemical field of the lost-circulation horizon within the Uvat suite.

4.3 Evaluation of Compatibility Between Waters Injected Into the AAC AS And Reservoir Waters

A number of indicators specified in sub. 3.2. are regulated for the waters injected into the lost-circulation bed. The indicators were generalized and assigned to two groups (before 2011 and after 2011). We further analyzed the indicators against the limit values set forth in the industry standard No. 39-225-88.

Such an analysis is the first step in evaluating if the waters can be injected based on the chemical criteria of quality. The second step is estimating the chemical compatibility of waters that are mixed in the bed. The injected and reservoir waters are considered chemically compatible under reservoir conditions (at specified temperatures and pressures) if the amount of sediment originated from their mixing does not exceed the values set out in the industry standard No. 39-225-88 "Water for Waterflooding of Oil Reservoirs. Estimation of Compatibility between Injected and Reservoir Waters Against Calcite and Gypsum", with reservoir properties of the lost-circulation horizon taken into account.

The chemical compatibility between the produced water to be injected and lost-circulation horizon water of the oilfield under study was determined by thermodynamic simulation of physicochemical processes occurring in the miscible waters by using the water chemical compatibility estimation software, in line with the industry standard No. 39-229-89 (Taranov et al., 2013).

The procedure is based on the relationship between the solubility of Ca and Mg salts in multicomponent blends and temperature, pressure and gas saturation of waters. The chemical composition of salt deposits is defined by the original composition of the reservoir and injected waters, with predominance of one or two types of salt, in which case the salt deposition is intense at a certain degree of dilution of reservoir waters. The following conditions underlie the procedure:

- The injected waters contain residual carbon dioxide that is enough for keeping carbonates dissolved.
- The waters are mixed under thermobaric conditions (120 atm pressure and + 50°C temperature) of the absorbing deposits.

The estimation used the following input data:

- 1) composition of mixed waters:
- 2) ratio of waters when mixed:
- 3) temperature of the system:
- 4) pressure of the system:
- 5) partial pressure of free CO₂.

The estimation procedure is detailed in.

The effect of the physical process of waterflooding on the variation in structural-mechanical properties of reservoir and on the oil displacement was examined in (Gimatudinov and Shirkovsky, 1971; Kotyakhov, 1977; Abyzaev et al., 1994; Gudok et al., 2007; Zheltov et al., 1981; Gladkov et al., 2012; Khavkin, 1998).

4.4 Stability Evaluation of Hydrogeochemical Measures of the Atlym-Novomikhailovsk Aquifer Complex

The fresh groundwaters of the Atlym-Novomikhailovsk aquifer complex are separated from the lost-circulation horizon by a thick mass of Turonian-Eocene siliceous-argillaceous rocks (750 m) that delimit the Cenozoic and Mesozoic aquifer basins. The vertical migration of injected substances through such a rock mass is almost ruled out, but despite some kind of natural protectability, a strict control is required for the quality attributes of fresh groundwaters of the aquifer complex within the area affected by injection sites of produced waters.

Here, we analyzed the time profile of the indicators such as salinity, dry residue, total hardness, content of petrochemicals, phenolic index and concentrations of anionic surfactants and chlorides (before injection and during injection) for fresh groundwaters of the Atlym-Novomikhailovsk aquifer complex. The listed indicators are the major markers of the process contamination of fresh groundwaters or of the possible ingress of mineralized waters into the aquifer complex containing freshwaters. Next, we evaluated the stability of the hydrogeochemical setting of the said aquifer complex.

5. RESULTS AND DISCUSSION

5.1 Evaluation of Natural Geologic-Hydrogeological Conditions of the AAC AS Within the Kamenny Subsurface Site

The natural geologic-hydrogeological conditions of the AAC AS within the Kamenny subsurface site conform to the current normative documentation:

1) the AAC AS is reliably isolated from overlying fresh groundwaters by the Turonian-Eocene siliceous-argillaceous aquiclude (K_{2t-d}) over 750 m thick, as mentioned hereinabove, and from the underlying Lower-Jurassic aquifer system by the Upper-Jurassic impermeable horizon about 300 m thick:

2) In addition, between the target Cenomanian horizon (the Uvat suite) and the subjacent Aptian horizon (the Vikulov suite) is the Albian aquiclude (enclosed in the Khanty-Mansyisk suite sediments) of over 130 m in thickness, creating a natural "barrier" in the AAC AS section and thereby separating the bottom of the AAC AS (Apt) from the lost-circulation horizon (Cenomanian). Together with the Palaeocene and Eocene sediments (P₁₋₂), the Albian aquiclude additionally isolates freshwaters of the Cenozoic aquifer basin from mineralized waters of the Lower-Jurassic aquifer complex.

3) In accord with the geophysical logging data, the effective thickness of the lost-circulation horizon is 278.4 m on average, with the total thickness ranging from 314.0 to 379.0 m and the mean being 366.6 m. The permeable lithological varieties are between 71.5 and 79.3%, averaging 76.1% of the total thickness, and are mostly composed of sandstones (72.5%), followed by 24.5% aleuritic-sandy rocks. The proportion of aleurolites is as low as 3.0%. The reservoir permeability of the object under exploitation varies from 18.93 to 48.99 mD within the site. The total water transmissibility of exploration wells varies from 8.2 m²/day to 21.6 m²/day, with the weighted mean across the field territory being 16.9 m²/day (16.6 m²/day as per the interference test data). Thus, the porosity & permeability properties of the Cenomanian horizon of the AAC AS warrant the required injectivity index for the injection of produced waters (co-extracted with oil) after appropriate conditioning.

5.2 Stability Evaluation of Hydrogeochemical Measures of the AAC AS Groundwaters by Monitoring Survey Results

The groundwater properties of the Aptian-Albian-Cenomanian aquifer complex on the territory of the Kamenny subsurface site were explored based on the study results of more than 90 standard samples collected between 1962 and 2017. The quality of the assay results of the groundwater samples was checked by the standard procedure (matching between total anions and total cations in the equivalent form, absence of above-limit indicators that are markers of drilling mud admixture, etc.). Based on the chemical analysis results of the Cenomanian horizon groundwater samples, we isolated three groups of observation periods: the 1960s (including the years 1962 and 1966), the 1980s (including the years 1985, 1988 and 1990) and the 2000s (including the years 2009, 2014 and 2017) (Table 3).

Table 3: Results of Monitoring Observations of Chemical Composition and Properties of the AAC AS Groundwaters

Indicator	Exploitation Years of Subsurface Site					
	1960s		1980s		2000s	
	Min.-Max.	Mean	Min.-Max.	Mean	Min.-Max.	Mean
Hydrogen ion concentration index, pH	N/A	N/A	6.0–7.0	6.5	6.7–8.4	7.9
Specific weight, g/cm ³	N/A	N/A	abs.	abs.	1.006–1.008	1.007
Salinity, g/cm ³	10.3–11.8	11.05	7.2–15.5	13.6	11.0–14.7	12.4
Total hardness, mg-eq./dm ³	5.0–10.5	8.0	6.8–15.5	11.6	11.0–16.0	14.3
<i>Macro-elements</i>						
Sodium+Potassium Na ⁺ +K ⁺ , mg/dm ³	3818.7–4260.0	4039.4	2515.0–5592.0	4227.0	3980.0–5640.0	4540.7
Magnesium Mg ²⁺ , mg/dm ³	21.4–24.0	22.7	14.0–82.0	39.7	36.0–62.0	51.1
Calcium Ca ²⁺ , mg/dm ³	60.1–174.4	117.3	104.0–244.0	174.6	140.0–240.0	200.9
Chlorides Cl ⁻ , mg/dm ³	5673.0–6407.2	6040.1	3621.0–8662.0	6398.3	6383.0–8330.0	7167.2
Sulfates SO ₄ ²⁻ , mg/dm ³	N/D	N/D	N/D–0.4	0.2	0.2–1.5	0–76
Bicarbonates HCO ₃ ⁻ , mg/dm ³	671.0–915.0	793.0	695.0–1366.0	1025.6	232.0–732.0	380.5
Carbonates, mg/dm ³	N/D	N/D	N/D	N/D	N/D–4.0	2.0
<i>Micro-elements</i>						
Iodine, mg/dm ³	11.1–12.8		6.1–14.9	12.4	8.9–10.6	9.8
Bromine, mg/dm ³	25.3–31.7	25.3	29.6–45.6	38.1	7.0–35.4	25.9
Boron, mg/dm ³	7.2–9.5	9.5	9.5–11.0	10.3	abs.	abs.
Iron, mg/dm ³	abs.	abs.	abs.–2.0	1.1	5.8–11.5	8.2

The sampling in those periods of time was associated with exploratory operations at the field or with calculation of groundwater reserves for the purpose of reservoir pressure maintenance, and was a part of the groundwater monitoring (for instance, the 2000s). For each period of observations, we estimated the means of chemical composition indicators including hydrogen ion concentration, specific weight, salinity, total hardness, macro- and micro-elements.

From the start of the exploration works, the salinity as one of the major composite indicators of the composition rose from 11.05 to 12.4 g/dm³, while it was 13.6 g/dm³ as per the analysis data in the 1980s. The average total hardness (which is estimated as total contents of calcium and magnesium in the equivalent form) also grew from 8.0 to 14.3 mg-eq./dm. Among the main salt-forming ions, the concentrations of sodium and potassium was observed to rise (from 4039.4 to 4540.7 g/dm³), as well as of chlorides (from 6040.1 to 7167.2 g/dm³). A minor tendency of a decline in the content of bicarbonate ions (from 793.0 to 380.5 g/dm³) was documented, evidencing a slight shift in the hydrogeochemical equilibrium in the water–rock system. No significant changes in the micro-elemental composition was detected, and only a slight increase in the iron concentration from the total absence to 8.2 g/dm³ (on average) can be noted. The analysis of changes in the concentrations of the said elements suggests that the lost-circulation horizon currently remains hydrogeochemically stable. Of course, it should be kept in mind that such a long-term period of observations involved assays performed by different laboratories using different instruments and procedures; however, in our view, the said central tendency of the preserved hydrogeochemical stability is quite clearly discernible. We have also come to such a conclusion by comparing the general hydrogeochemical background of the Cenomanian horizon of the AAC AS in the survey area (Abdrashitova and Salnikova, 2021) (i.e. major indicators of the chemical composition of the Cenomanian horizon groundwaters of the neighboring Vodorazdelnoye, Talinskoye, Pottymsko-Inginskoye, Em-Egovskoye and Palianovskoye fields): the mean salinity of the Cenomanian horizon across the Krasnoleninsky district is 13.1 g/dm³, which is close to 12.4 g/dm³ within the Kamenny subsurface site.

We previously reported the results of decade-long monitoring surveys of the AAC AS (16 injection sites) within the Khanty-Mansiysk Autonomous District in Tyumen Oblast (Salnikova, 2021), where the overall volume of produced water injected into the AAC AS is 196.2 million m³ for the entire

exploitation period of the sites. Based on the chemical assay results of groundwaters (3185 samples) from the start of exploration works at the field through to present, we have come to a conclusion that the hydrogeochemical setting of the aquifer system is stable and no considerable changes in the chemical composition, ratio of major salt-forming elements and other indicators are occurring, but there are minor fluctuations. The stability of the setting is probably attributed to the geologic-hydrogeological peculiarities of the AAC AS that embraces huge mineralized water reserves thanks to which the intrusions of injected waters do not significantly shift the hydrogeochemical equilibrium. That said, it should be realized that the Cenomanian horizon is a deep water-bearing horizon and a part of the natural eco-system, and is colossally exposed to the human's engineering activity. The horizon is almost inaccessible for field survey and observation. Many researchers note (Glynn and Plummer, 2005) that source data on the geological medium and hydrogeological setting of deep petroleum horizons can be known only with some degree of conditionality, and their simulation is performed with some assumptions and simplicities. Therefore, one should seek to take into account all the possible indicators and reactions illustrative of the variable hydrogeochemical setting of the horizon (Appelo and Postma, 2005; Bethke, 1996). The approaches to monitoring the AAC AS groundwaters and controlling the status of rocks and groundwaters must continuously be upgraded and improved.

5.3 Evaluation of compatibility between waters injected into the AAC AS and reservoir waters

The industry standard controls and sets limits for a series of injected water indicators whose values can be the judge of the feasibility and preparedness of the waters for injection into the bed (Table 4).

Findings from the study performed in 2018 demonstrate that the injected produced waters comply with the industry standard's requirements by hydrogen ion concentration index (7.1–7.2), oxygen and hydrogen sulfide contents (absent), iron (III) ions (0.2–1.3 mg/dm³), and swelling ability (absent).

The salinity of the injected produced waters (18.0 mg/dm³ on average, control samples as of 2018) is somewhat higher than that of the Uvat suite water (12.3 mg/dm³ on average). Thus, no increase in the swelling ability of the clay constituent of the productive sediments is foreseeable.

Table 4: Content of Elements to be Limited in Produced Water at the Kamenny Subsurface Site

Quality Attributes	Limits by industry Standard No. 39-225-88	Survey Period	
		Before 2011	After 2011
		16 samplings	4 samplings
pH value	within 4.5–8.5	6.8–7.3	6.6–8.0
Dissolved oxygen, mg/dm ³	below 0.5	N/D–0.40	N/D–0.65
Hydrogen sulfide, mg/dm ³	not permissible	N/D–0.82	N/D–1.70
Iron (III) ions, mg/dm ³	not permissible if injected water contains H ₂ S	0.2–1.3	0.2–26.2
Mechanical impurities, mg/dm ³	3.0	73.2–117.8	17.6–168.0
Petrochemicals, mg/dm ³	5.0	2.2–10.6	0.8–33.0 and higher
Swelling ability of clay minerals in bed	abs.	abs.	abs.
Corrosion severity	At most 0.1 mm/year	from 0.1 to above 0.5	above 0.5

Iron (III) was quantified to be 0.2–1.3 mg/dm³, which may lead to an increased content of mechanical impurities in the injected waters, as described in sub. 3.2. The content of this element should be monitored in the future.

The analysis carried out herein showed that the following indicators exceed the established norms:

- mechanical impurities (17.6–127.0 mg/dm³) whose content is somewhat higher than that of the last year;
- the quantity of petrochemicals (2.2–10.6 mg/dm³) in one sample exceeds the norm but is significantly lower than those found previously;
- the rate of corrosion whose projected value will be above 0.5 mm/year because coefficient K_x that takes account of the impact of chemical factors was calculated by the procedure described in the Ruling Document No. 39-

0147323-339-89-R “Guidelines for Design and Exploitation of Pipeline Corrosion Protection of Petroleum Gathering System at West-Siberian Fields” and is 1.9–2.2; the waters are referred by the severity of aggression to a highly aggressive medium.

In that case, measures will be required to normalize the above-listed indicators to meet the industry standard's requirements.

The second step of evaluating if the waters can be injected based on chemical quality criteria was the calculation of the chemical compatibility between the injected and reservoir waters.

The estimation of the chemical compatibility between the reservoir and injected waters by calculating the carbonate balance of the system was underpinned by chemical assays of the samples from reservoir water (well no. 9305) and produced water from compressor and pumping station CPS-2 at the Kamenny subsurface site. We carried out these calculations while

conducting works to justify if the Cenomanian horizon of the AAC AS can be used as the lost-circulation horizon.

The reservoir waters at the field contain almost no sulfates or they content is low, therefore we do not consider the sulfate balance. The compatibility of the waters was evaluated from the data on the status of the system of their blends.

The characterization of reservoir waters of the Cenomanian lost-

circulation horizon is outlined in sub. 2.1 and of injected waters in sub. 2.2.

The thermodynamic simulation results (under conditions: 120 atm reservoir pressure and +50°C reservoir temperature) with a varied ratio of injected and reservoir waters in their blend are summarized in Table 5. For each ratio of injected and reservoir waters, we estimated the content of sediment-forming constituents: calcium, magnesium, carbonate alkalinity values, saturation degree of the resultant blend when the waters are mixed, as well as CO₂ saturation pressure.

Table 5: Evaluation Outcome of Possible Carbonate Sedimentation When the Produced Water and the Uvat Suite Reservoir Water are Mixed at the Kamenny Subsurface Site

Portion of water in the Blend, %		Content of Sediment-Forming Constituents, g/dm ³			Degree of Saturation	Sediment, g/dm ³	Salinity, g/dm ³	CO ₂ Saturation Pressure, Atm
Reservoir	Injected	Ca	Mg	Carbonate alkali				
(well no. 9305)	(CPS-2)							
100	0	0.205	0.056	0.354	0.999	0	12.48	0.215
80	20	0.205	0.055	0.515	1.390	0.119	13.57	0.178
60	40	0.205	0.053	0.676	0.566	0	14.66	0.142
50	50	0.206	0.053	0.757	0.723	0	15.21	0.124
30	70	0.206	0.051	0.918	1.294	0.117	16.30	0.087
10	90	0.206	0.05	1.079	2.680	0.323	17.39	0.051
0	100	0.206	0.049	1.160	4.063	0.389	17.93	0.032

The simulation results demonstrate that the content of salt-forming ions (calcium and bicarbonate) and the salinity of the resultant blend are increased and the quantity of Mg ions is decreased by the injection of produced water. The blend is observed to be stable when the ratios of reservoir and produced waters are 60:40 and 50:50. The sediment originates when the injected water portion is 20% and 70% and higher.

The injected produced waters are instable under thermobaric conditions of the lost-circulation bed and can generate a calcite sediment at 323.0 mg/dm³ when the portion of injected waters attains 90% in the blend.

The resultant quantitative measures of sedimentation should be viewed as limit values, as the calculation methodology does not account for enrichment of the blend with productive bed carbon dioxide and for temperature variation because of colder injected waters coming into the subsurface. The occurring physicochemical process will be dependent on the advance rate of injected waters across the bed and on their ratio to the reservoir water. The calcite deposition along the travel way of fluids is the most probable for the bottom-hole formation zone. It can be noted by tracing the behavior of the carbonate system under reservoir conditions that the sediment is predicted to fully dissolve as the injected waters are advancing across the bed and the CO₂ saturation pressure is equalizing towards the reservoir pressure (Table 6).

Table 6: Variation in the Quantity of Calcite Sediment Under Reservoir Conditions (The AAC AS Beds) at the Kamenny Subsurface Site

Ratio of reservoir water to injected water	100:0	80:20	60:40	50:50	30:70	10:90	0:100
Quantity of calcite sediment, g/dm ³	0	0.098	0	0	0	0.037	0.104

5.4 Stability Evaluation of Hydrogeochemical Measures of the Atlym-Novomikhailovsk Aquifer Complex

To evaluate how much the injection site of produced waters forming wastewaters affect fresh groundwaters, we used the results from hydrogeochemical surveys performed in the periods before water injection into the AAC AS and in the exploitation period. In accord with the applicable Russian Sanitary Rules and Norms (the Russian SanPiN) No. 1.2.3685-21 "Hygienic Standards and Requirements for Ensuring the Safety and (or) Harmlessness of Environmental Factors for Humans", we evaluated physicochemical properties and the content of some contaminants (phenols, anionic surfactants, etc.).

The fresh groundwater extraction at the Kamenny subsurface site is being performed for the purpose of production and engineering water-supply to oil facilities with the aid of 32 wells. In terms of location, the wells are grouped into 11 water-intake sites located in the northern and southern parts of the licensed site. Freshwater-intake wells at the booster pump station BPS-1, which are the nearest to the wastewater injection site, may undergo the highest man-made burden. The evaluation results demonstrate no significant changes in the chemical composition of the aquifer complex, with minor fluctuations in the indicators being due to the natural hydrogeochemical features of the Oligocene-quaternary aquifer

system of the West-Siberian megabasin (Table 7).

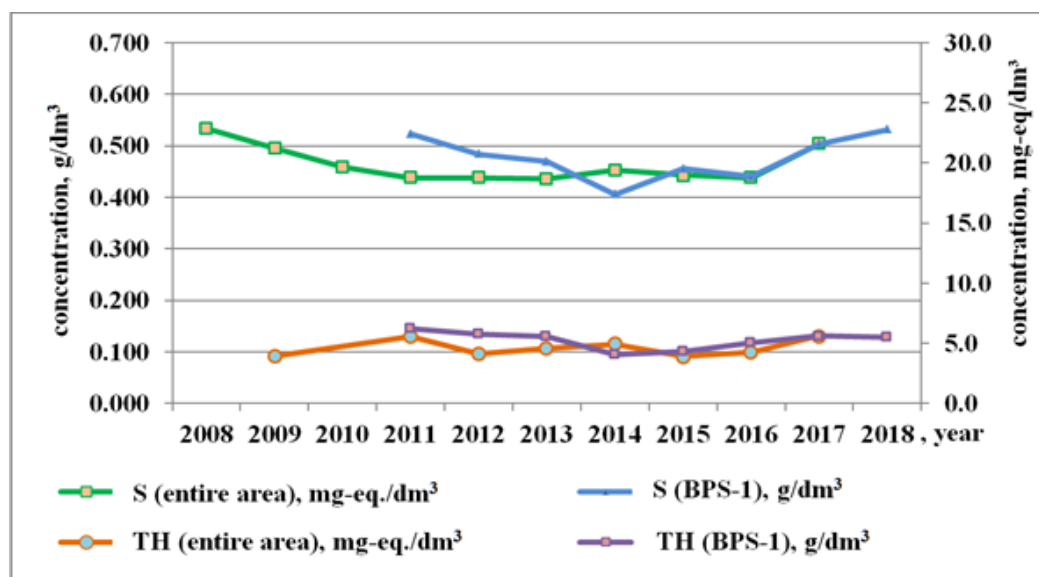
The average content of petrochemicals in the groundwaters goes over the limit (SanPiN No. 1.2.3684-21). This excess was also documented prior to the injection, which is likely due to the operation of the field infrastructure. The petrochemicals content during the injection is not observed to rise further. Overall, the excess is negligible and can be eliminated by water-conditioning actions. As per the 2018 monitoring data, the content was 0.043 mg/dm³, not in excess of the maximum permissible concentration (0.1 mg/dm³).

The phenolic index was determined to be negligible, from <0.0005 to 0.0102 mg/dm³ and was not in excess of the maximum permissible concentration of 0.25 mg/dm³ in the 2018 sampling as per the monitoring data. The content of anionic surfactants in the fresh groundwaters does not exceed the maximum permissible concentration of 0.5 mg/dm³ and was below 0.025 mg/dm³ in 2018. The content of chlorides in the freshwaters of the field ranges from <0.78 to 6.8 mg/dm³, not in excess of the maximum permissible concentration (350.0 mg/dm³).

The observable variations in salinity (S) and total hardness (TH) (Fig. 5) are within permissible limits and due to the regional peculiarities of the water genesis, such as area geology, different levels of mineral solubility of the natural environment, water-intake impact and several other factors not related to the man-caused contamination.

Table 7: Some Indicators of Fresh Groundwaters of the Atlym-Novomikhailovsk Aquifer Complex at the Kamenny Licensed Site

Indicators	Limits by SanPiN No. 1.2.3684-21	Observation Periods	
		Before injection	During injection
pH	6.0–9.0	6.0–6.9	6.05–8.80
Salinity calcd., g/dm ³	up to 1.0	-	0.300–0.531
Dry residue, mg/dm ³	up to 1000	217.0–320.0	195.0–358.0
Total hardness, mg-eq./dm ³	up to 7.0–10.0	-	3.48–6.40
Petrochemicals, mg/dm ³	up to 0.1	0.110–0.130	<0.02–0.110
Phenolic index, mg/dm ³	up to 0.25	N/D	<0.0005–0.01020
Anionic surfactants, mg/dm ³	up to 0.5	N/D–0.080	<0.025–0.025
Chlorides, mg/dm ³	up to 350	2.1–6.8	0.78–4.90

**Figure 5:** Year-Wise Variations in Groundwater Salinity (S) and Total Hardness (TH) at the Kamenny Subsurface Site. BPS-1, Booster Pump Station No. 1

It follows from the study findings that the chemical composition and properties of fresh groundwaters at the kamenny subsurface site are not undergoing any appreciable changes, and the observable deviations are due to the regional peculiarities and long-lasting exploitation of the horizons, and are not associated with the impact of the produced water injection site, giving grounds for the prognosis that the waters will retain the quality in the future.

The observations of the aquifer complexes should be further continued.

6. CONCLUSIONS

The results of our studies to examine the safety in use of the Aptian-Albian-Cenomanian aquifer system (AAC AS) for the purpose of produced water injection at the Kamenny subsurface site in West Siberia have afforded positive solutions to the problems posed herein.

1. The geologic-hydrogeological conditions of the AAC AS within the Kamenny site are suitable for use of the Cenomanian horizon as the lost-circulation horizon because it is some kind of being naturally "isolated" from overlying fresh groundwater horizons such as the regional Turonian-Eocene aquiclude over 750 m thick and from subjacent horizons by the Upper-Jurassic aquiclude rocks lying below the AAC AS and being about 300 m thick. Also, the natural aquiclude "barrier" (over 130 m) in the AAC AS section additionally separates the AAC AS bottom (the Apt) from the lost-circulation horizon (the Cenomanian). Besides, the AAC AS is areally persistent not only within the kamenny subsurface site but also throughout West Siberia. It has quite high porosity & permeability properties that provide the required water injectivity index.

2. The stability evaluation of hydrogeochemical indicators of the AAC AS groundwaters by the chemical assay results from the 1960s to 2015–2017 evidences that the lost-circulation horizon currently retains hydrogeochemical stability. Some evaluated indicators such as groundwater salinity, total hardness, and concentrations of sodium, calcium and chlorides for the specified period of observations had risen negligibly, but the rise in values is in the range of fluctuations in the regional hydrogeochemical background of the Krasnoleninsky district.

3. The chemical stability between the reservoir and injected waters was evaluated in two steps: injected water quality assessment and chemical compatibility assessment of the reservoir and injected waters. The chemical composition of the injected waters was analyzed against several indicators regulated by normative documentation. The analysis has discovered that the contents of mechanical impurities and petrochemicals and the rate of corrosion development go over the established norms. The said indicators can be brought to the norms by water-conditioning actions. The estimation of the chemical compatibility between the injected and reservoir waters by calculating the carbonate balance demonstrated that the injected produced waters are instable under thermobaric conditions of the lost-circulation bed and can generate a maximum calcite sediment of 323.0 mg/dm³ at a 10:90 ratio of reservoir and injected waters. The fluids can be injected into the Cenomanian horizon only after appropriate water conditioning. The appropriate water conditioning prior to injection has widely been trialled and in use for quite a long time in the West-Siberian petroleum region, therefore the design of such actions causes no difficulties to the subsurface user.

4. The evaluation of hydrogeochemical attributes of the Atlym-Novomikhailovsk aquifer complex that are markers of possible man-caused fresh-groundwater contamination or possible ingress of mineralized waters into the aquifer complex showed no impact of produced water injection over time.

Thus, the findings evidence the consistence of our hypothesis of the safe use of the AAC AS for injection of produced waters. But despite the positive solutions obtained for all the research problems posed herein, we want to put emphasis on the need for continuously upgrading the monitoring system for both the lost-circulation horizon and the overlying ones, as well as on the need for scrupulous compliance with all of the environmental safeguards—which is prerequisite for preserving the natural balance of the subsurface resources of the West-Siberian petroleum region.

ACKNOWLEDGMENTS

This article was prepared as part of the Digital Core technology project at the West Siberian Interregional World-class Science and Education Centre.

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