International Journal of Energy Production and Management
https://www.acadlore.com/journals/IJEPM

Analysis of Oil and Gas Technogenesis of the Aptian-Albian-Cenomanian Hydrogeological Complex of the West Siberian Mega Basin

Yulia I. Salnikova[1,2], Rimma N. Abdrashitova[2*], Leila A. Abukova[3], Albert Zaliatdinov[4], Mikhail G. Poluyanov[5]

[1] Laboratory of Petroleum Hydrogeology, Industrial University of Tyumen, 625000 Tyumen, Russia
[2] Department of Geology of Oil and Gas Fields, Industrial University of Tyumen, 625000 Tyumen, Russia
[3] Laboratory of Oil and Gas Geofluid Dynamics, Oil and Gas Research Institute, Russian Academy of Science, 119333 Moscow, Russia
[4] Center for Scientific and Technical Research, Almetyevsk State Technological University – Higher School of Oil, 423462 Almetyevsk, Russia
[5] Underground Water and Underground Structures Department, State Commission for Mineral Reserves, 119333 Moscow, Russia

[*] Correspondence: Rimma N. Abdrashitova (abdrashitovarn@tyuiu.ru)

Received: 07-05-2025 **Revised:** 08-12-2025 **Accepted:** 09-10-2025

Citation: Y. I. Salnikova, R. N. Abdrashitova, L. A. Abukova, A. Zaliatdinov, and M. G. Poluyanov, "Analysis of oil and gas technogenesis of the Aptian-Albian-Cenomanian hydrogeological complex of the West Siberian mega basin," *Int. J. Energy Prod. Manag.*, vol. 10, no. 3, pp. 523–534, 2025. https://doi.org/10.56578/ijepm100313.

Abstract: Produced water during oil production from wells is a major environmental pollution concern. The treatment to bring the water to an environmental standard level is very costly. This article is devoted to one of the environmental safety issues associated with the development and operation of oil fields in central Western Siberia. The research methodology included monitoring the condition of the Apt-Alb-Cenomanian hydrogeological complex of the Mesozoic basin, producing statistical data, and proposing a solution to reduce the produced water pollution. Cite detection results found that the complex is composed of sandy-silt deposits, with the roof lying at depths of 900 m and a thickness of approximately 850 m. The total volume of water extracted from the complex for the research area for the purpose of maintaining reservoir pressure in 2024 amounted to 388.33 million m^3, with 315.424 million m^3 of excess water extracted during production being utilized by the Apt-Alb-Cenomanian hydrogeological complex. A technogenic water exchange was formed within the complex. The article analyzes the results of long-term hydrogeochemical monitoring of the Apt-Alb-Cenomanian hydrogeological complex at three oil fields with a long history of exploitation. The relative stability of hydrogeochemical conditions is shown to be preserved, probably due to the natural capacity of the complex. At present, it is necessary to develop new control criteria that take into account large-scale technogenic water exchange.

Keywords: Associated waters; Formation waters; Hydrogeochemistry; Oil and gas technogenesis; West Siberian megabasin

1 Introduction

Monitoring the state of the underground hydrogeosphere during the development of hydrocarbon fields is an integral part of subsurface use in all oil and gas-producing regions of the world. Due to the increasing scale and diversity of anthropogenic impacts on the geological environment, groundwater is subject to irreversible changes in its original composition, which in turn have negative consequences for the fluid-bearing rocks and overlying aquifers used for water management purposes. Of course, produced water is also used to maintain reservoir pressure in productive horizons, but the surplus produced is many times greater than the amount needed to provide the reservoir pressure maintenance system. Oil and gas technogenesis covers all systems of the geological environment from the surface to deeply buried productive oil- and gas-bearing horizons. Wu and Tang [1], Clark and Berryman [2], He et al. [3], and many other authors emphasize the need to consider and assess environmental risks for surface, groundwater (including fresh drinking and mineralized water), and rocks in the development and exploitation of hydrocarbon deposits.

Rational use of water resources nowadays acquires a new meaning, in particular for oil and gas producing regions with a long history of development – it is the functioning of all oil and gas production facilities in the conditions of natural and technological systems operating for decades.

Geological and hydrogeological studies of oil- and gas-bearing areas of the West Siberian megabasin are rather extensive. However, despite this, environmental studies of the underground hydrosphere are often scattered or are carried out only within the scope of the requirements of licenses for subsurface use of hydrocarbon deposits. As a rule, these are sampling for reduced chemical analysis once a quarter, once a year, for control analysis, as well as measurements of reservoir pressures, temperatures, and well technical condition checks. Researchers realize that the cumulative impacts on all components of the geologic environment are large-scale and long-lasting, but there are no indicators of impacts beyond those adopted back in the late 1980s.

Assessment of the ecological vulnerability of the subsurface hydrosphere not only contributes to the rational implementation of environmental management measures and long-term protection of the fragile ecological environment but also provides the necessary scientific basis for rational development and efficient allocation and management of resources [4].

When developing effective indicators of oil and gas technogenesis, we consider it important to assess the real current situation in the West Siberian megabasin. In the work of Kazanenkov et al. [5], devoted to the development of oil production directions in Russia, it is stated that the ongoing deterioration of geological conditions of hydrocarbon prospecting is due to the need to increase the depth of exploration work, the transition to complex deposits and hard-to-recover reserves, and the increase in the water cut of recoverable products. This situation is similar in many oil and gas-producing regions of the world [6–8]. Despite the general trend of increased attention and control of the environmental situation, the main goal of oil-producing organizations remains to increase the oil recovery factor [9]. This, in turn, entails the need for additional anthropogenic impact on the subsurface: the use of more potent oilfield chemistry, an increase in the number of hydraulic fractures, and the volume of disposal of excess produced water into the subsurface. Each of these impacts on the subsurface requires precise monitoring and assessment. For example, the need to utilize surplus produced water or produced water is one of the constant challenges for subsurface users in the West Siberian oil and gas producing region. These are those waters that are separated from oil by oilfield chemicals. It is known that this type of wastewater contains organic and toxic substances such as benzene, toluene, ethylbenzene, and xylenes, inorganic components such as heavy metals, polyaromatic hydrocarbons, and alkylphenols [10–12], also dissolved and suspended solids, chemicals that are separated in process plants, and other pollutants. For example, the current situation with surplus produced water in the central part of the West Siberian megabasin is characterized by a constant increase in the volume of water to be disposed of. However, in the region under study, these waters are only monitored for a limited list of indicators prior to disposal.

Scientists and specialists in the field of rational subsurface use and geology note the urgent need to improve industry standards and departmental regulatory documents on the content and presentation of the results of operational observations of all components of the geological environment during hydrocarbon production [13]. Jamil and Al-Kayiem [14] proposed and analyzed a downhole produced water dumping in the low-pressure zone using hydrocyclonic oil/water separation in the downhole. The developed procedure successfully simulated the production zone and the interaction of the oil and water in a natural environment where the reservoir pressure is the sole driving force. The model could be an essential tool to assist in the prediction of the behavior of oil/water mixture flow in the wellbores, and to serve in designing downhole oil/water separators.

For the central part of the West Siberian oil and gas producing region, three main areas of impact of oil and gas technogenesis should be identified: the Oligocene-Quaternary complex containing fresh water in the upper horizons; the Apt-Alb-Cenomanian hydrogeological complex (AAC HC), and deeper horizons containing oil. This study focuses on the AAC HC. This is precisely the hydrogeological complex from which millions of cubic meters are extracted annually for formation pressure maintenance (FPM), and into which surplus water extracted alongside oil is injected. The relevance of the study is justified by the fact that, as a rule, buffer horizons such as the AAC HC for excess associated and wastewater, located at great depths, are often given little attention. This is due to the fact that exposure at great depths (around 1000–2000 m) presumably does not have a direct negative impact on the upper aquifers, which are valuable for drinking and domestic water supply. However, the flow of contaminated water through the annular space from deep horizons to higher ones is quite possible.

The study aims to assess the level of impact of oil and gas technogenesis on the Apt-Alb-Cenomanian hydrogeological complex. To achieve the main aim of the study, the following research objectives have been identified:

•Analysis of the geological structure and hydrogeological conditions of the AAC HC in the central part of the West Siberian oil- and gas-bearing region;

•Assessment of the scale of technogenic water exchange due to water extraction from the AAC HC and placement of excess associated water extracted;

•Assessment of changes in the hydrogeochemical conditions of the complex based on long-term observations of key indicators of the chemical composition of the complex's waters.

•Proposals for a list of necessary criteria for assessing the transformation of the complex under the influence of oil and gas technogenesis.

2 Methodology of Research

The research methods included the following steps:

Step-1. Systematization and collection of data on the volumes of water withdrawal from the AAC HC to ensure FPM, and on the volumes of utilization of excess associated water in the AAC HC for the main fields in the study area, as well as specifically, for three selected oil fields, A, B, and E, with a long history of operation.

Step-2. Analysis of changes in groundwater indicators of the AAC HC based on the results of long-term monitoring for selected deposits.

Step-3. Analysis of types of oil and gas technogenesis in the hydrogeological complex under study, making it possible to propose a list of areas for monitoring the condition of the complex in order to preserve the natural balance within its boundaries.

Table 1. Standard timing and regulations adopted by the monitoring management of the AAC HC

Parameter Under Monitoring	Timing and Regulations
Measurement of water withdrawal/accounting for the volume of wastewater pumped	Daily
Measurement of the level of the operating complex (dynamic level with fixed well flow rate, static level)	Monthly
Measurement of pressure in the intertube space	Monthly
Water sampling to determine the chemical composition of groundwater (Cl, HCO_3, CO_3, SO_4, Ca, Mg, Na, K, pH, $O_{(gsol)}$, Fe)	Once every 4 months
Sampling of water for mechanical impurities and petroleum products	Once every 4 months
Conducting a trial pumping operation with measurement of its flow rate and detailed monitoring of the decrease and restoration of the dynamic level	When conducting inventory revaluation
Measuring the water temperature at the mouth of the water intake well	Once every 4 months
Presence of leaks, technical malfunctions, water metering and pumping equipment, and measurement of bottomhole depth (technical condition of the well)	Yearly

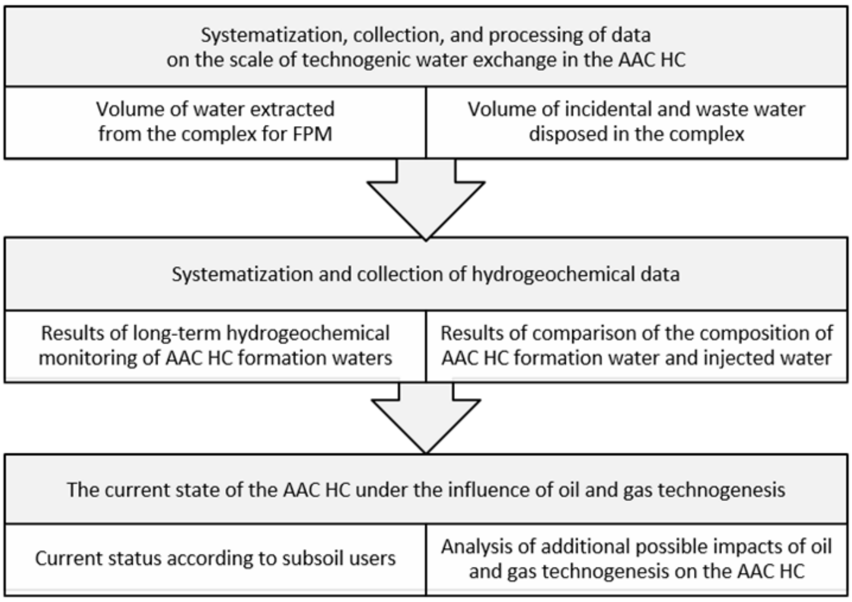

Figure 1. Flowchart of the research methodology

The data collection procedure consisted of obtaining data from subsoil users in the region on the conduct of monitoring management at hydrocarbon fields. In accordance with Russian legislation governing the use of mineral resources, the license holder is required to carry out monitoring activities as specified in the monitoring program. An approximate list is provided in Table 1.

The relative limitations of the data presented are related to the smaller volume of available data than is necessary, since during the monitoring process, the number of samples and the list of components to be determined are determined by the monitoring program in accordance with the subsoil use license and rarely exceed its limits. Of particular interest could be data from extended microbiological analysis, the content of residual oilfield reagents, which inevitably enter the formation with the excess produced water that is disposed of. A flowchart of the research process, based on data provided by subsoil users of the fields during the period of field operation, is presented in Figure 1.

To accomplish the research objectives, data on production capacity from the AAC HC (25 fields) and utilization volumes (14 fields) in the central part of Western Siberia over the past 10 years were used. In addition, 1061 results of chemical analyses of AAC HC formation waters from three selected fields (268, 675, and 118, respectively), with a long history of operation. The analysis of hydrogeochemical data included the rejection (removal) of analyses accepted for reservoir waters of oil and gas fields, the results of which indicated, for example, impurities from drilling fluids, technical wastewater, or clearly poor-quality water sampling. During the study, temporary graphs were constructed showing changes in the concentration of the main macrocomponents over the period of operation of the selected deposits, as well as graphs showing changes in the mineralization parameter of the AAC groundwater. Temporary monitoring made it possible to track the dynamics of changes in the hydrogeochemical conditions of the AAC HC under the influence of oil and gas technogenesis.

3 Geological and Hydrogeological Setting of the Study Area

The studied area is joined to the central part of the West Siberian Plate, as shown in Figure 2. The geological structure of the area is represented by a folded basement and sedimentary cover. The basement is composed of metamorphosed and highly dislocated rocks of Precambrian and Paleozoic age. Terrigenous rocks of the sedimentary cover, whose thickness reaches 3–4 kilometers or more, lie on the basement sediments with sharp angular and stratigraphic inconsistencies. The surface of the foundation sinks from the sides of the geosyncline to its central and northern regions.

Figure 2. Location of the research area

The thickness of the sedimentary cover is 3100–3500 m, the oil saturated layer is about 800 m, which unites the Neocomian and the upper part of the Jurassic sediments. The depth of the deposits is 2000 to 2900–3000 m. A typical geological structure of the central part of Western Siberia is shown in Figure 3.

The West Siberian hydrogeological megabasin is identified as a supra-ordinal underground water reservoir within the West Siberian geosyncline. In the megabasin section, 7 hydrogeological complexes were identified: Oligocene-Quaternary, Turonian-Paleogene, Aptian-Albian-Cenomanian, Neocomian, Upper Jurassic, Middle Lower Jurassic, and Triassic-Paleozoic [15].

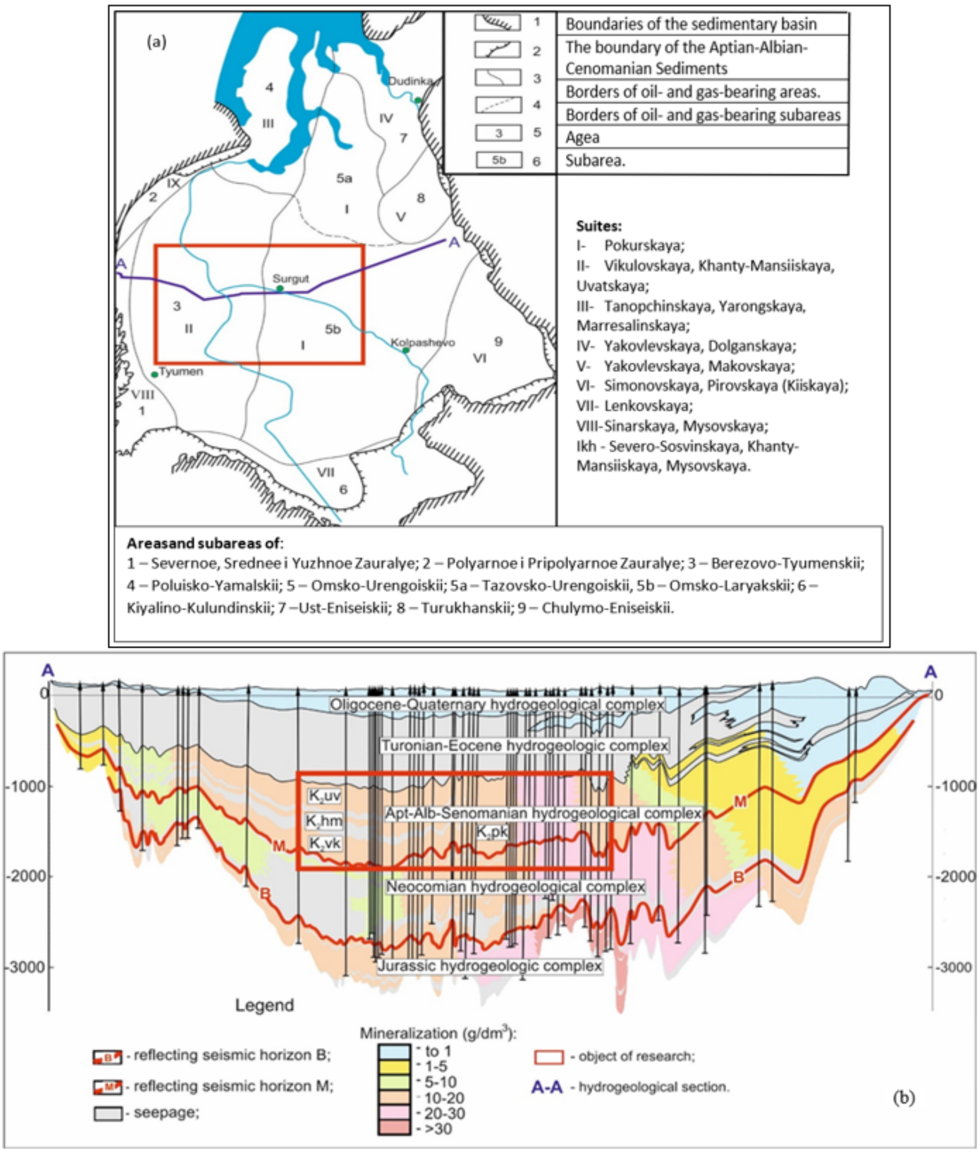

Figure 3. Schematic geological map: (a) distribution of the AAC HC; (b) hydrogeological section A-A

The waters of the Apt-Alb-Cenomanian hydrogeological complex are high-pressure, with excess pressure at the mouth of 1–7 atm. Well flow rates are most often 100–800 m^3/day (up to 2000–3000 m^3/day). The waters of the complex are widely used to maintain the formation pressure of exploited oil-bearing formations. In the central part of the West Siberian megabasin, depression craters have formed with a radius of tens of kilometers and a decrease in levels to tens and the first hundreds of meters.

The Neocomian hydrogeological complex is extremely heterogeneous in terms of the structure and relationship of aquifers and impervious strata. The thickness reaches 500–650 m in the central part of the basin. In terms of ion-salt composition and salinity, the groundwater of the Neocomian complex does not fundamentally differ from the waters of the Aptian-Albian-Cenomanian complex. Water salinity is 20–25 g/dm^3.

The Jurassic hydrogeological complex reaches a thickness of up to 1000 m and is characterized by reduced water availability (specific flow rates of 0.005–0.01 dm^3/s·m). The ion-salt composition of the formation waters is quite diverse.

4 Results and Analysis

4.1 The Scale of Technogenic Water Exchange Within the Study Area

Man-made transformations of the natural environment have long occupied the minds of scientists and specialists, and the issues of technogenesis are discussed at forums in relation to various components of the Earth's landscape shell. Technogenesis is penetrating deeper into the Earth's crust. The penetration of technogenesis into the Jurassic horizons and basement is associated with the depletion of reserves of upper productive oil reservoirs in the Cretaceous sediments of Western Siberia. Groundwater, as the most active component of the geological environment, reacts quickly to any external interference. A man-made hydrogeological field with parameters different from its natural state is beginning to form. The transformation of the natural field takes place in all its components, including hydrodynamic, hydrogeothermal, and hydrogeochemical.

In the study area, as in the whole of Western Siberia, the AAC HC is significantly affected by technogenesis associated with oil field exploitation processes. The extent of the impact of oil and gas technogenesis on the AAC AC is determined by the extent of technogenic water exchange within the complex. On the one hand, this involves selecting water to ensure the functioning of the FPM system, and on the other hand, it involves the utilization of excess associated water in the complex. Information was collected on these two parameters for the fields in the study area over the past ten years. These volumes are shown graphically in Figures 4 and 5.

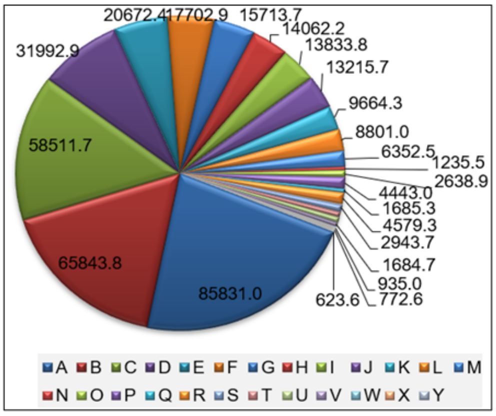

Figure 4. Volume of water extracted from the AAC HC to supply the FPM system since the start of field development, thousands m^3

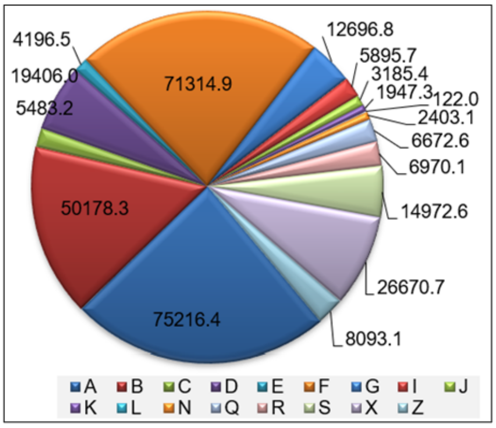

Figure 5. Volume of utilization in the AAC HC of excess associated water, thousand m^3

The names of the deposits are shown as letters, which are related to the terms of use of this information by subsoil users. The letters used to designate the fields are the same in Figure 4 and Figure 5.

The scale of technogenic water exchange due to water extraction from the AAC HC and the placement of excess water extracted along with it is enormous. Due to the increase in oil water content, these values are expected to rise further.

4.2 Assessment of Changes in the Hydrogeochemical Conditions of the AAC HC Based on Long-Term Observations

To assess the transformation of hydrogeochemical conditions in the AAC HC, hydrogeochemical data were collected and systematized for three oil fields in the study area (fields A, B, and E in). The conditions and duration of operation (long-term withdrawal of water from the AAC HC and disposal of excess water extracted in the process at this complex), as well as hydrogeochemical monitoring data for these deposits, made it possible to analyze changes in the indicators of groundwater in the AAC HC. Table 2 shows the values of water withdrawal from the AAC HC and utilization in this complex for the observation period at fields A (2001–2024), B (2004–2024), and E (2000–2022).

Table 2. Indicators of the scale of technogenic water exchange for the AAC HC within oil fields A, B, and E

Indicators of the state of the AAC HC	Deposit A	Deposit B	Deposit E
Volume of water extracted from the complex in 2024, thousand ^{3}	85831.0	65843.8	20672.4
Volume of associated water stored in the complex in 2024, thousand ^{3}	75216.4	50178.2	4196.5

Figure 6 shows the changes in the concentrations of the main salt-forming ions for deposits A (6a), B (6b), and E (6c). Figure 7 (a, b, c) demonstrates the change in mineralization in the formation waters of the AAC HC, respectively.

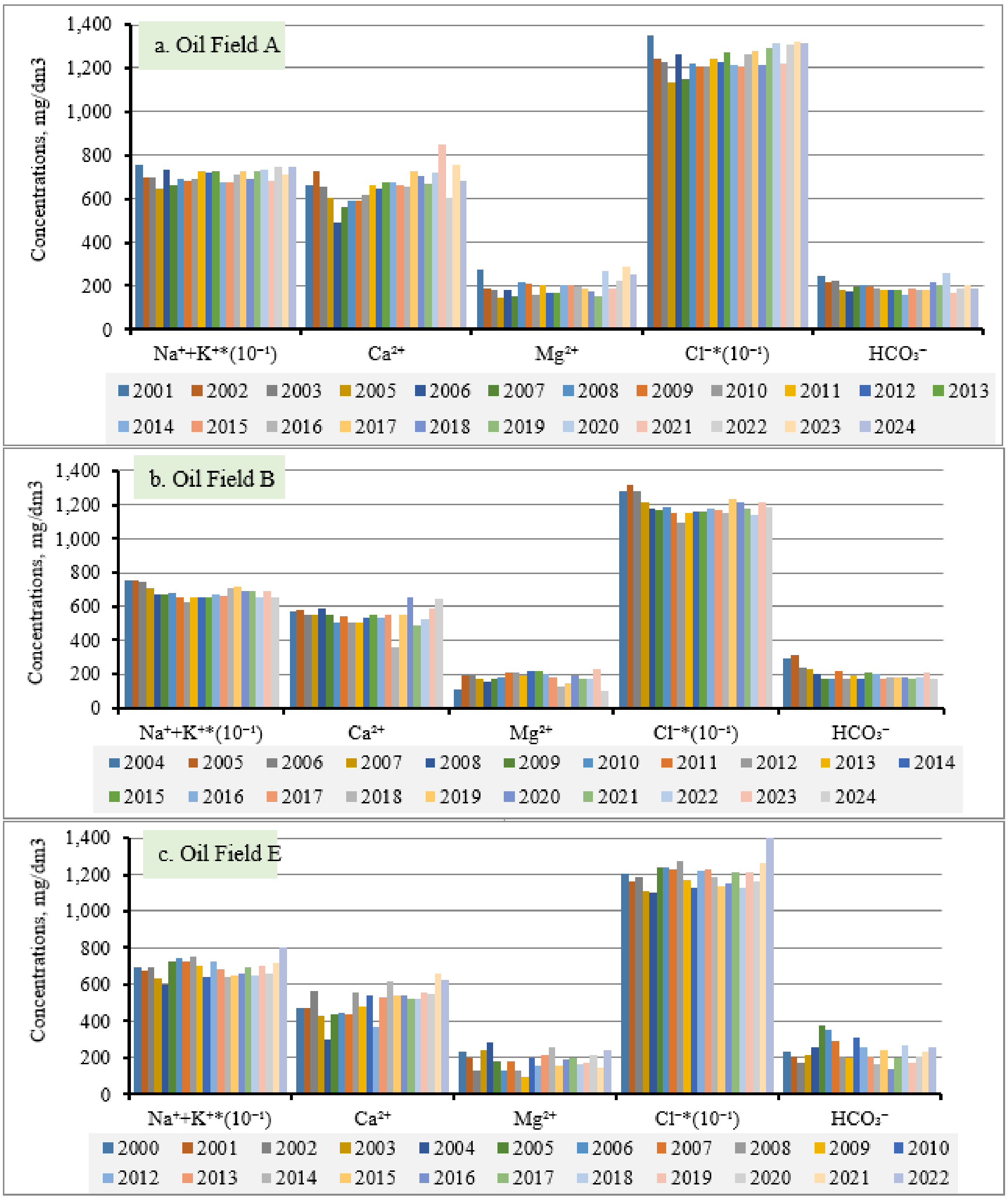

Figure 6. Changes in the concentrations of the main salt-forming ions in the formation waters of the AAC HC deposits A(a), B(b), and E(c)

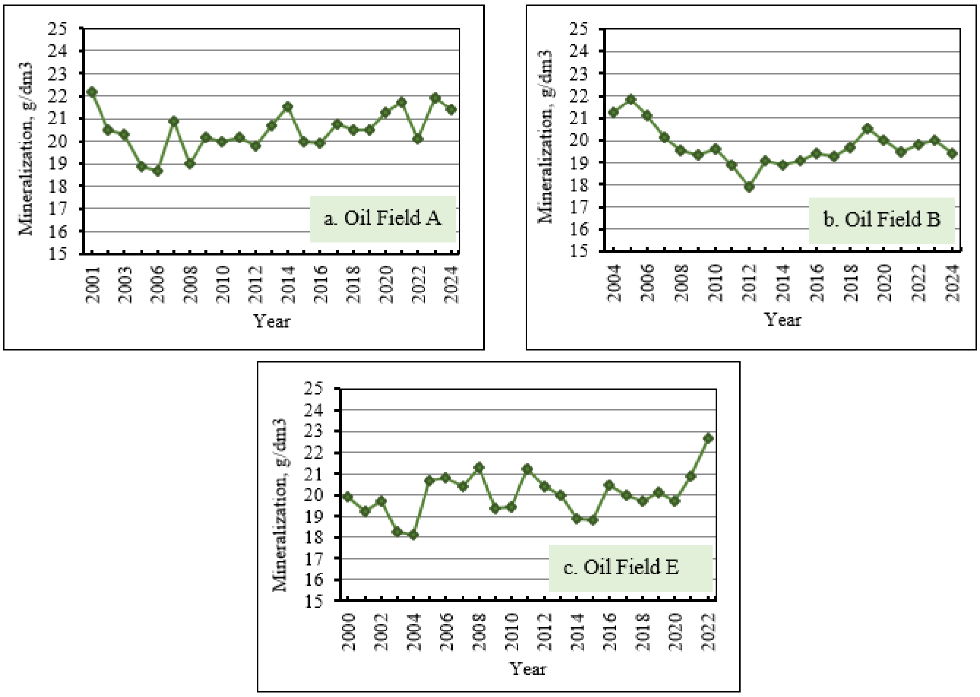

Figure 7. Changes in the mineralization in the formation waters of the AAC HC deposits A(a), B(b), and E(c)

Table 3. Concentrations of major salt-forming ions in the waters of the AAC HC

Deposit	**A**		**C**		**E**	
Year	**2001**	**2024**	**2004**	**2024**	**2000**	**2022**
M, g/dm^3	22.2	21.4	21.3	19.4	19.9	22.7
$Na^+ + K^+$, mg/dm^3	7555.5	7466.2	7518.0	6526.0	6935.3	8032.4
Ca^{2+}, mg/dm^3	661.4	686.3	574.3	646.5	467.6	627.9
Mg^{2+}, mg/dm^3	273.6	252.9	113.7	102.6	231.0	239.1
Cl^-, mg/dm^3	13471.0	13122.5	12762.0	11875.8	12053.0	14180.0
HCO_3^-, mg/dm^3	244.0	189.2	296.7	176.9	235.9	258.3
Number of samples	268		675		118	

Table 4. Comparison of the composition of formation and injected water: deposit A

Composition Indicator		**Formation AAC HC**	**Associated Water (Injected into the Reservoir)**
Hydrogen index, pH		7.4	6.3
Mineralization, g/dm^3		22	27.9
Salt composition, mg/dm^3	Sodium, Na^+	7198	7521
	Potassium, K^+	–	–
	Calcium, Ca^{2+}	639	1102
	Magnesium, Mg^{2+}	185	122
	Sulfates, SO_4^{2-}	–	–
	Chlorides, Cl^-	12702	13826
	Bicarbonates, HCO_3^-	186	122
	Carbonates, CO_3^{2-}	–	–
Total hardness, mg-eq/dm^3		47.1	65
Content of petroleum products, mg/dm^3		1.97	58
Mechanical impurities, mg/dm^3		41	68
Iron (III) ions, mg/dm^3		3.2	2.98

In general, despite significant technogenic water exchange, shown in Table 2, the ratio of the main salt-forming ions remained unchanged in the formation waters of the AAC HC, shown in Figure 6, which is also shown in Table 3, where the values of the main components in the first and last years of observations are given.

It is believed that he preservation of the natural balance of the AAC groundwater under the influence of significant oil and gas technogenesis is explained by the significant natural capacity of the complex. Large rock thicknesses, of about 850 m, and a lithological composition consisting mainly of sandstones with high porosity ranging from 12% to 42% and permeability up to 12,000 mD. At the same time, high water pressures are likely to compensate for the significant water withdrawal required for the operation of the FPM system.

The entire AAC HC of the study area is characterized by significant volumes of water utilization. However, this type of oil and gas technogenesis impact has not had a significant impact on natural hydrogeochemical conditions as recorded by existing monitoring programs. This is attributed to the similar chemical composition of the AAC HC reservoir waters and the injected associated waters from the underlying Neocomian and Jurassic complexes. A comparison of the compositions of formation and injected water for fields A, B, and E is given in Table 4, Table 5, and Table 6, based on parameters controlled as standard during utilization. Parameters that differ significantly between formation water and produced water are highlighted in bold.

Table 5. Comparison of the composition of formation and injected water: deposit B

Composition Indicator		Formation AAC HC	Associated Water
Hydrogen index, pH		7.7	6.7
Mineralization, g/dm^3		14.2	44.4
Salt composition, mg/dm^3	Sodium, Na^+	4645	15856
	Potassium, K^+	28	–
	Calcium, Ca^{2+}	600	1263
	Magnesium, Mg^{2+}	182	208
	Sulfates, SO_4^{2-}	< 2	–
	Chlorides, Cl^-	8510	26942
	Bicarbonates, HCO_3^-	183	134
	Carbonates, CO_3^{2-}	< 6	–
Total hardness, mg-eq/dm^3		44.9	74
Content of petroleum products, mg/dm^3		0.56	23.2
Mechanical impurities, mg/dm^3		< 6	72
Iron (III) ions, mg/dm^3		1.2	0.57

Table 6. Comparison of the composition of formation and injected water: deposit E

Composition Indicator		Formation AAC HC	Associated Water
Hydrogen index, pH		7.4	6.8
Mineralization, g/dm^3		19.4	24.4
Salt composition, mg/dm^3	Sodium, Na^+	7425	9851
	Potassium, K^+	52	117
	Calcium, Ca^{2+}	506	317
	Magnesium, Mg^{2+}	118	60
	Sulfates, SO_4^{2-}	< 12.5	30.9
	Chlorides, Cl^-	12478	15456
	Bicarbonates, HCO_3^-	183	738
	Carbonates, CO_3^{2-}	< 2	< 2
Total hardness, mg-eq/dm^3		34.9	20.8
Content of petroleum products, mg/dm^3		0.32	33.2
Mechanical impurities, mg/dm^3		8.8	30.8
Iron (III) ions, mg/dm^3		2.1	1.9

Formation and injected waters are sodium chloride in terms of ion composition in all fields under consideration. In general, we observe elevated concentrations of petroleum products, often mechanical impurities, in the deposits under consideration. Potentially, if such water enters the AAC HC on the scale described above, it could lead to formation clogging, water contamination, and temperature reduction. Formation temperatures are measured only at the initial stage of the construction and equipment of wells. They were 55.4℃, 43.7℃, and 43.2℃ for deposits A, B, and E, respectively. The extent of utilization of associated waters, which are cooled when they rise to the Earth's surface, suggests some cooling of the AAC HC groundwater, but no such studies have been conducted yet. It should be understood that AAC HC waters, which at the present stage are already a mixture of formation and injected waters (as a result of the described technogenic water exchange), constantly enter the productive formation during FPM production. Unfortunately, the list of modern studies conducted in sufficient quantity to identify patterns is limited by the monitoring program in accordance with the subsoil use license.

4.3 Proposed Assessment and Characterization Criteria

The Apt-Albian-Cenomanian hydrogeological complex is characterized by a wide variety of possible manifestations of technogenesis, especially when it is simultaneously used as a source of water supply for the FPM system and as a lost circulation horizon for wastewater injection.

The results of the study show the relative hydrogeochemical stability of the complex's groundwater, which is explained by its significant resources, good filtration and storage properties, and the volume of water-bearing rocks in the complex. We consider this situation to be temporary and require monitoring. Once a certain threshold is reached, irreversible consequences may ensue. The chain of changes may be as follows: water extraction, pressure and head reduction, wastewater injection, changes in the salinity and composition of water, interaction of injected water with rocks, leading to mechanical coloration of suspended particles and chemical coloration of pores formed by calcite sediment, resulting in a change in permeability and porosity.

In the work of Liu et al. [16], it is indicated that the composition of the formation waters of the deposit (using the example of Fengcheng Formation, Mahu Depression, Xinjiang, China) is preserved under the condition of good natural tightness and overlap of the horizon. Nevertheless, it can be disturbed by migration along the paths created by natural and man-made ways, for example, by hydraulic fracturing of the formation. Many authors see the main danger of using a buffer horizon in the possible migration of contaminated waters into the overlying fresh horizons valuable for water supply. For example, Lgotin and Makushin [17] conducted a study in the area of the city of Tomsk (Russia) on the possible migration of radionuclides and other toxic components from the absorbing aquifer used for waste disposal into the Paleogene aquifer complex used for water supply. Despite the fact that there is a significant clay aquifer and an unused aquifer buffer between the aquifer systems, there are indications that such migration between aquifers may occur either due to sand windows in the aquifer or due to insufficiently sealed borehole rings. Good protection parameters characterize the studied AAC HC; it is hopefully covered by overlying sediments and is located at a sufficient depth. However, unfortunately, leaks in the annular space may also occur, given the relatively long service life of wells in the study area [18].

Taking into account the current data and results, the following parameters of changes in the natural state of AAC HC due to the extraction and utilization of excess water extracted during production can be identified as changes in levels of formation pressures and changes in the natural hydrogeochemical conditions of the complex. It is necessary to develop new parameters for monitoring the condition of AAC HC for inclusion in the license agreements of subsoil users of oil fields, primarily in the following areas:

•Recording changes in the filtration and storage properties of complex rocks.

•Microbiological composition control.

•Control of residual oilfield reagent content.

•Control of water flow into upstream aquifers.

5 Conclusions

The results of studies conducted in the research area show that the scale of the impact of oil and gas technogenesis on the AAC HC is enormous. The total volume of Apt-Cenomanian water selected for FPM purposes for 2024 was significant—388.33 million m^3, and 315.424 million m^3 of associated water was injected (utilized) into the AAC HC. At the same time, the analysis of changes in the hydrogeochemical conditions of the AAC HC at three selected fields with long-term operation showed a relative preservation of the composition, which is probably explained by the natural capacity of the complex. Given the scale of the impact, there is likely to be a limit to the observed stability of natural conditions, and it is necessary to introduce new criteria for monitoring the condition of the complex in a timely manner. The natural hydrogeosphere performs the most important function, stabilizing the state of the geological environment in the conditions of oil and gas technogenesis.

Funding

The results presented in the article were partially obtained through state budget funding for the research project "Geological justification of optimal conditions for natural and induced in-situ hydrogen generation and its underground storage in depleted hydrocarbon deposits and salt structures" (No. NIOKTR (ROSRID) 125021302095-2).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] X. Wu and S. Tang, "Comprehensive evaluation of ecological vulnerability based on the AHP-CV method and SOM model: A case study of badong county, China," *Ecol. Indic.*, vol. 137, p. 108758, 2022. https://doi.org/10.1016/j.ecolind.2022.108758

[2] K. J. Clark and K. R. Berryman, "Assessing long-term stability of the geological environment," in *Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Waste*, 2017, pp. 195–227. https://doi.org/10.1016/b978-0-08-100642-9.00008-6

[3] D. He, K. Hou, X. X. Li, S. Q. Wu, and L. X. Ma, "A reliable ecological vulnerability approach based on the construction of optimal evaluation systems and evolutionary tracking models," *J. Clean. Prod.*, vol. 419, p. 138246, 2023. https://doi.org/10.1016/j.jclepro.2023.138246

[4] A. Ferreira, A. Pereira, N. Rodrigues, J. Barbosa, and P. Leitão, "Integration of an agent-based strategic planner in an enterprise service bus ecosystem," in *2015 IEEE 13th International Conference on Industrial Informatics (INDIN)*, Cambridge, UK, 2015, pp. 1336–1341. https://doi.org/10.1109/INDIN.2015.7281929

[5] V. A. Kazanenkov, I. V. Filimonova, and V. Y. Nemov, "Major directions and tasks of oil and gas searches in Western Siberia for next decades," *Drill. Oil*, vol. 10, pp. 10–18, 2019.

[6] F. Nath, M. O. S. Chowdhury, and M. M. Rhaman, "Navigating produced water sustainability in the oil and gas sector: A critical review of reuse challenges, treatment technologies, and prospects ahead," *Water*, vol. 15, no. 23, p. 4088, 2023. https://doi.org/10.3390/w15234088

[7] R. K. Muslimov, "On a new paradigm for the development of the oil and gas complex in Russia," *Oil Ind. J.*, no. 3, pp. 8–13, 2021. https://doi.org/10.24887/0028-2448-2021-3-8-13

[8] I. V. Sharf, D. N. Borzenkova, and L. S. Grinkevich, "Tax incentives as the tool for stimulating hard to recover oil reserves development," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 27, p. 012079, 2015. https://doi.org/10.1088/1755-1315/27/1/012079

[9] A. Muggeridge, A. Cockin, K. Webb, H. Frampton, I. Collins, T. Moulds, and P. Salino, "Recovery rates, enhanced oil recovery and technological limits," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 372, p. 20120320, 2014. https://doi.org/10.1098/rsta.2012.0320

[10] M. A. Al-Kaabi, N. Zouari, D. A. Da'na, and M. A. Al-Ghouti, "Adsorptive batch and biological treatments of produced water: Recent progresses, challenges, and potentials," *J. Environ. Manag.*, vol. 290, p. 112527, 2021. https://doi.org/10.1016/j.jenvman.2021.112527

[11] F. Al-Ajmi, M. Al-Marri, F. Almomani, and A. AlNouss, "A comprehensive review of advanced treatment technologies for the enhanced reuse of produced water," *Water*, vol. 16, no. 22, p. 3306, 2024. https://doi.org/10.3390/w16223306

[12] C. L. Conrad, Y. B. Yin, T. Hanna, A. J. Atkinson, P. J. Alvarez, T. N. Tekavec, M. A. Reynolds, and M. S. Wong, "Fit-for-purpose treatment goals for produced waters in shale oil and gas fields," *Water Res.*, vol. 173, p. 115467, 2020. https://doi.org/10.1016/j.watres.2020.115467

[13] S. A. Olaleye, P. O. Isibor, D. O. Agbontaen, T. O. Imoobe, and I. I. Kayode-Edwards, "Impacts of oil and gas exploration," in *Arctic Marine Ecotoxicology*, 2024, pp. 195–209. https://doi.org/10.1007/978-3-031-73584-4_9

[14] H. H. Al-Kayiem and I. E. A. Jamil, "Fundamental investigation of the oil/water flow emulsion in the downhole by CFD simulation," *WIT Trans. Ecol. Environ.*, vol. 224, pp. 541–551, 2017. https://doi.org/10.2495/ESUS170501

[15] V. M. Matusevich, L. Kovyatkina, G. Pozdeeva, and V. Popov, "Theoretical principles of petroleum hydrogeology of the West Siberian megabasin (WSMB)," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 33, p. 012051, 2016. https://doi.org/10.1088/1755-1315/33/1/012051

[16] J. Liu, X. Zhang, X. Luo, R. Zhu, and J. Dick, "Geochemistry of formation water and its implications for petroleum source rocks in the Fengcheng Formation, Mahu Depression, Xinjiang, China," *Front. Earth Sci.*, vol. 9, p. 774501, 2022. https://doi.org/10.3389/feart.2021.774501

[17] V. Lgotin and Y. Makushin, "Groundwater monitoring to assess the influence of injection of liquid radioactive waste on the Tomsk public groundwater supply, Western Siberia, Russia," *Geol. Soc. Lond. Spec. Publ.*, vol. 128, no. 1, pp. 255–264, 1998. https://doi.org/10.2118/206506-MS
[18] I. V. Filimonova, I. V. Provornaya, A. V. Komarova, and E. A. Zemnukhova, "Sustainable trends in the regional structure of oil production in Russia," *Oil Gas Geol. Theory Pract.*, vol. 14, no. 3, p. 4, 2019. https://doi.org/10.17353/2070-5379/33_2019

Nomenclature

AAC HC	Apt-Alb-Cenomanian hydrogeological complex
FPM	Formation pressure maintenance
A, B, C, Y	Encrypted name of oil field