Integrated environmental risk assessment and climate resilience framework for water-saturated reservoirs: A petrophysical approach with cross-continental applications

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Abstract. This study explores the dual benefits of carbon capture and storage (CCS) and geothermal energy from water-saturated reservoirs in the Seloken field, Chad Basin, Nigeria. A relative analysis with insights from Russia's West Siberian Basin was made. Petrophysical analyses used well-log data to characterize three formations. CO_2 storage capacity, geothermal output, and seal integrity were analyzed. Porosity (Ø = 22–31%), water saturation (Sw = 96–100%), and shale volume (Vsh = 1.3–6.5 API) were obtained. The Kerri-Kerri Formation is the best CCS option with high porosity (31%) and net thickness (270–500 m), though its storage capacity is lower than the Achimov Formation (West Siberia) due to thinner seals. Geothermal potential (1.2-2.0 MW/km²) was identified in reservoirs with high bulk volume water (0.277-0.299). Microbial-induced calcite precipitation (MICP) was recommended to enhance sealing units. The Kadaru-1 well was identified as suitable for hydrogen storage. These findings highlight the role sedimentary basins could play in GHG reduction. The work provides actionable insights to help achieve Nigeria's Nationally Determined Contribution (NDC) by adopting relevant Russian Federation best practices for sustainability.

1 Introduction

The growing danger of climate change is driving the world toward cleaner, low-carbon energy solutions. Carbon capture and storage (CCS) is helping move towards low or zero-carbon economies [1,2]. CCS refers to the process of isolating CO_2 emissions and storing them subsurface geologic formations like depleted reservoirs or saline aquifers [3,4]. CCS is also an approach used to separate CO_2 emission by injecting them into brown (old oil and gas) fields or underground water layers (water-saturated aquifers). According to Yahia et al. [5], keeping CO_2 in storage sites for a long time depends on several natural geological

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processes and the trapping style mechanism (structural or stratigraphic). Essentially, solubility trapping helps CO_2 slowly mix with the fluids in the rock over time; also, residual trapping keeps CO_2 stuck in the pore spaces due to the cohesive forces [6]. Mineral trapping helps keep CO_2 permanently stored by causing chemical reactions that turn CO_2 into solid carbonate minerals, but this usually takes a very long time, like thousands or millions of years.

Conversely, structural and stratigraphic trapping supports CO_2, which is trapped in thick, impermeable subsurface layers (caprocks) which seal and prevent an upward movement of gas from the reservoirs. The safety of storing carbon dioxide in the subsurface depends on the rock features, layers, and the sealing units that hold it in place [7]. A solid trapping system requires an appreciable storage space, moderate fluid movement, and a strong caprock to stop leaks. At the same time, the types of minerals in the reservoir play a key role in transforming CO_2 into solid minerals and help keep the storage system chemically stable over time.

The general practice in the evaluation of hydrocarbon-bearing formations is to characterize petrophysical parameters, such as shale volume (Vsh), porosity (Ø), and water saturation (Sw) [8]. For clean formations, water saturation can be calculated using the simple conductivity model of Archie's equation. However, the presence of clay minerals in shaly sand reservoirs increases conductivity, which tends to bias the computed water saturation.

Hanson et al. [9] argued that the evolution of CCS has created a platform for energy transition, which refers to a major structural change in energy supply and consumption in an energy system. Loschetter et al. [10], opined that energy transition is preceded by a challenging environment with the adoption of novel approaches in water-saturated reservoirs management and storing excessive CO_2, which is harmful to our atmosphere.

Furthermore, studies such as Malozyomov et al. [11] and Fisher et al. [12] have shown that water-saturated reservoirs ($Sw \geq 96\%$) are mostly associated with formations where the capillary forces are insufficient to displace a significant amount of water by hydrocarbons, or where the reservoir is in the water leg below the oil-water contact. These reservoirs basically cause environmental concerns and can be leveraged for climate change mitigation through CCS to prevent gas flaring. The integration of petrophysical characterization and climate resilience studies is a frontier believed to help in developing reservoir management, which makes our study relevant by identifying oil-producing countries, climate change controls, and basins with multiple enormous water-saturated reservoirs.

Therefore, our study aims to bridge the existing gap between water-saturated reservoirs and climate change resilience by developing a cutting-edge framework of the Seloken field, Chad Basin, Northeastern Nigeria. We intend to identify and measure risks through petrophysical characterization, assess the chances of repurposing reservoirs for climate change mitigation, and create international applications through the GHG reduction initiatives of the Russian Federation.

2 Methodology

2.1 Study Area and Data Collection

The Seloken Field is found in the Chad Basin, Northeastern Nigeria. Four exploratory wells have been drilled within the field, which include: Bulte-1, Kasade-1, Herwa-1, and Kadaru-1. The Bulte-1 and the Kasade-1 wells are located in the Southeastern part of the study area, while the Herwa-1 and Kadaru-1 wells were drilled in the Northeastern part of the Seloken Field. The Seloken Field lies within 11.5° 30`N and 14° 40`N and longitude 11° 45` E and 14° 45`E. The Bulte-1 and Kasade-1 wells are closer to the Upper Benue Trough and Zambuk Ridge than the other two wells. Fig. 1 shows the base map of the study area.

These formations display a wide range of properties with Sw ≥ 96%. Furthermore, data from four (4) wells, as shown in Fig. 2, were evaluated through the integration of GR log (GR), bulk density log (RHOB), and deep induction resistivity logs (ILD). Our study revolved around three major geologic formations (Kerri-Kerri (Reservoir B), Chad (Reservoir C), and Gongila (Reservoir A).

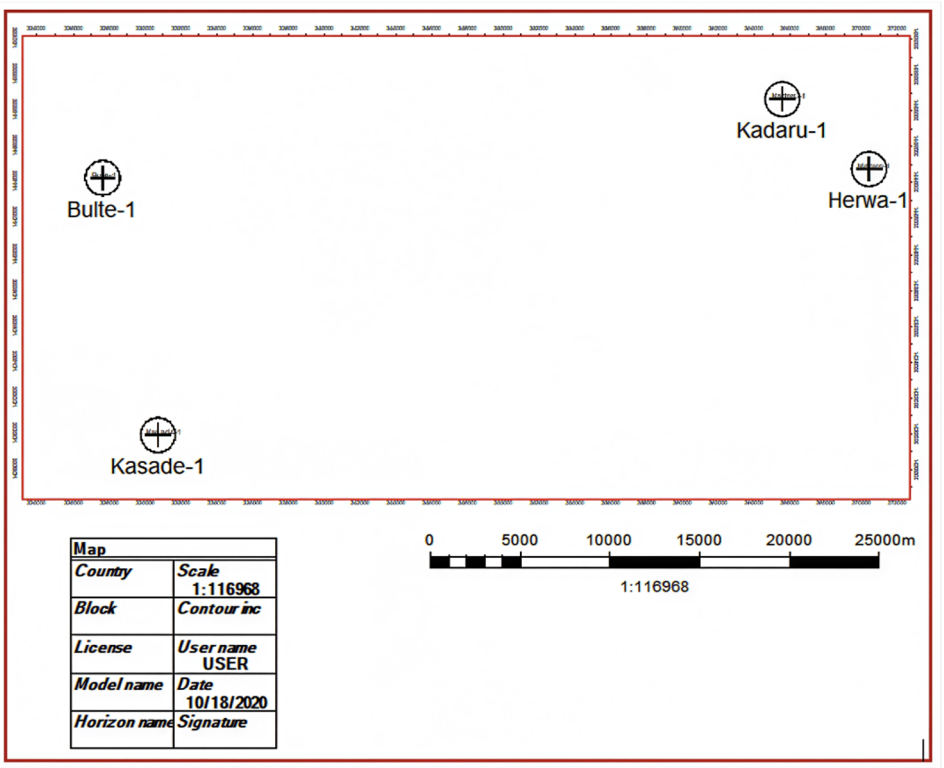

Fig. 1. Base map of the study area showing the positions of the four wells

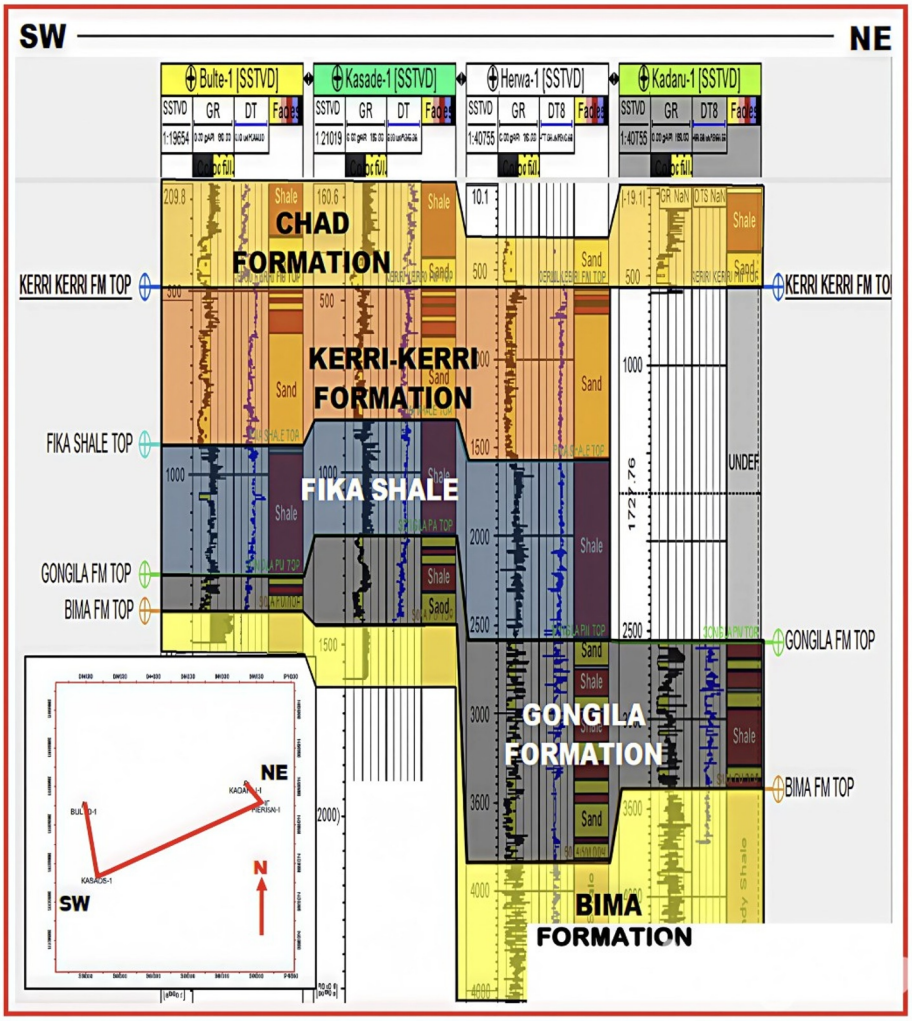

Fig. 2. Well logs showing the geologic formations across four wells

2.2 Petrophysical Parameter Calculation

2.2.1 Determination of Volume of shale (Vsh)

The Gamma-ray (GR) log is used for the evaluation of Vsh (equation 1), a record of the total count of natural radioactivity of the formation traversed by the borehole. GR logs reflect the clay or shale content of the formation since they contain abundant radioactive elements such as uranium, potassium, and thorium. It can be employed for stratigraphic identification, lithologic correlation and workover operations.

A property that affects both the formation characteristics and logging tool response is known as shaliness. It is because of Vsh's role in the computation of essential petrophysical properties such as water saturation and porosity [13]. Gamma Ray index (IGR) can be computed with the formula in equation (2):

Shale Volume (Vsh) was determined from gamma ray logs using the Larionov method in equation (1):

$$V_{sh} = 0.083\ (2^{3.7*IGR} - 1) \qquad (1)$$

Where;

$$IGR = \frac{GR_{max} - GR_{min}}{GR - GR_{min}} \qquad (2)$$

2.2.2 Determination of porosity (Ø)

The density log is a type of porosity log that helps in evaporite identification, gas detection, determination of hydrocarbon density, evaluation of complex lithology, oil-shale yield determination, overburden pressure calculation, and computation of rock mechanical properties. The density logs measure the electron density of the formation via backscatter of gamma-rays, which is related to the True bulk density by the following equations 3 and 4:

$$\rho_a = 1.0704\ \rho_b - 0.1883 \qquad (3)$$

Where;

ρ_a = apparent bulk density

ρ_b = bulk density

However, for water filled formation

ρ_a = ρ_b

To determine the total porosity using density log, the following formula was used;

$$\emptyset_d = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \qquad (4)$$

Where; ρma = 2.65 g/cm³ (matrix density for sandstone), ρ b = bulk density from RHOB logs, and ρf =1.0 g/cm³ (formation fluid density).

Effective porosity: The formula used to compute the effective porosity is shown in equation (5):

$$\emptyset_{eff} = \emptyset_{total} * (1 - V_{sh}) \qquad (5)$$

Where; Vsh = Volume of Shale

$Ø_{tota}$ = Total Porosity

$Ø_{eff}$ = Effective Porosity (Fadiya *et al.,* [14])

Water saturation: For the uninvaded zone, according to Archie formular in Glover [15], the S_w and hydrocarbon saturation (S_h) can be calculated with equations 6 and 7:

$$\boldsymbol{S_w = \left(\frac{a * R_w}{R_t * \emptyset_m}\right)^{\frac{1}{n}}} \qquad (6)$$

$$\boldsymbol{S_h = 1 - S_w} \qquad (7)$$

Where Sw = water saturation; Ro = resistivity of a water filled formation; Rt = true formation resistivity (that is, deep induction); Rw = resistivity of formation water at formation; Φ = porosity; n = saturation exponent usually taken as 2.0; m = cementation factor; a = tortuosity factor

Bulk Volume Water (BVW) was calculated as:

$$BVW = \emptyset * S_w \qquad (8)$$

CO_2 Storage Capacity was estimated using:

$$M_{CO_2} = \emptyset\,(1 - S_w) * h * \rho CO_2 * 10^{-3} \quad (9)$$

with ρ CO_2 = 700 kg/m³.

2.3 Risk Assessment Framework

Environmental risks were categorized and quantified based on petrophysical thresholds:

I. Groundwater contamination risk: High when Rt < 25 Ωm and Sw > 95%
II. Geomechanical instability: High when Ø > 25% and Vsh < 3.5 API
III. Seal integrity for CCS: Good when Vsh > 3.5 API

3 Results and Discussion

3.1 Petrophysical Characterization

The analysis revealed distinct petrophysical characteristics across the three formations (Table 1). The Kerri-Kerri Formation (Reservoir B) exhibited the highest porosity (28–35%) and consistent high water saturation (99.95–99.99%), resulting in BVW values of 0.277–0.299. The Chad Formation (Reservoir C) showed moderate porosity (21–34%) with Sw ranging from 96.00% to 99.91%, yielding BVW values of 0.202–0.337.

The Gongila Formation (Reservoir A) has lower porosity (7–27%) and consistently high Sw (96.00–100%), with BVW values of 0.202–0.270. From the results obtained, we can conclusively say that reservoirs C and B have good to excellent petrophysical properties, as shown in the histogram and bubble plots in Fig. 3. The high Sw indicates that the reservoirs are almost devoid of oil and gas, hence, they can be repurposed for CCS.

Table 1. Summary of the petrophysical parameters by Formation

Formation	Porosity Range (%)	Sw Range (%)	BVW Range	Dominant Characteristics
Kerri-Kerri (B)	28–35	99.95–99.99	0.277–0.299	High porosity, excellent connectivity
Chad (C)	21–34	96.00–99.91	0.202–0.337	Variable porosity, good thickness
Gongila (A)	7–27	96.00–100	0.202–0.270	Lower porosity, high shale content

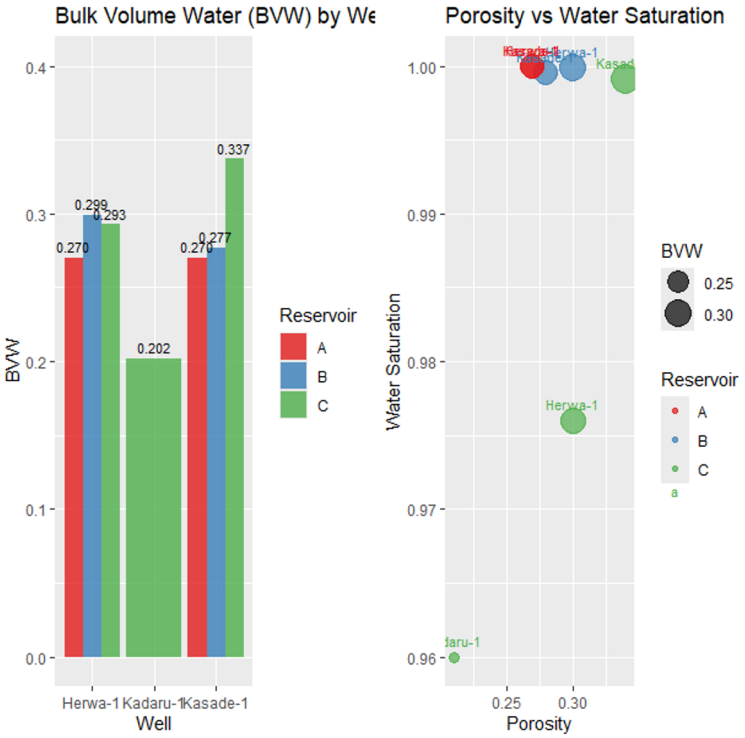

Fig. 3. Histogram showing BVW by well and a bubble plot showing porosity vs Sw

3.2 Environmental Risk Assessment

Our studies analyzed three possible risk factors (groundwater contamination, geomechanical instability, and wastewater disposal) that could impact potential CCS in the Seloken field. From our observations, we inferred that there could be high chances for groundwater contamination due to low resistivity (<25 Ωm) and high Sw (>95%) readings. However, continuous resistivity monitoring and construction of an aquifer protection zone are potential remediation techniques that could prevent leachates or other contaminants from infiltrating into the reservoirs. Other risk factors and their mitigation strategies are shown in Table 2, while the heat map in Fig. 4 shows high impacts for all three identified risk factors.

Table 2. Environmental risk factors, indicators, and mitigation strategy

Risk Factor	Impact	Key Indicators	Mitigation Strategy
Groundwater Contamination	High	Low Rt (<25 Ωm), high Sw (>95%)	Continuous resistivity monitoring, aquifer protection zones
Geomechanical Instability	High	High Ø (>25%), low Vsh (<3.5)	Density log monitoring, controlled reinjection
Wastewater Disposal	High	High BVW (>0.25), limited injectivity	Porosity-permeability evaluation, treatment protocols

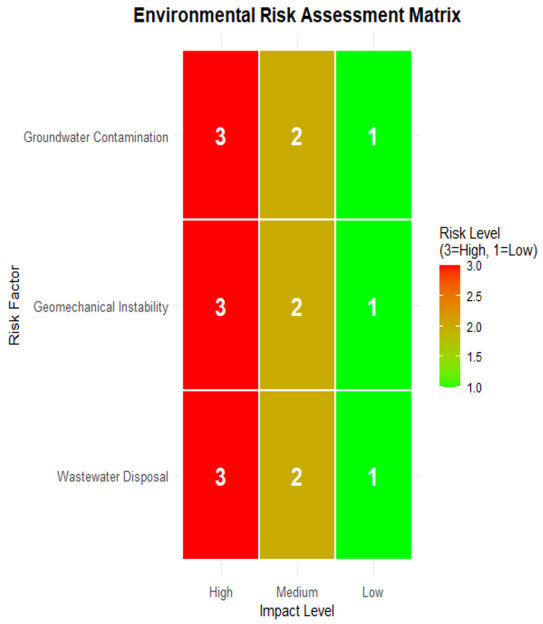

Fig. 4. A heat map showing the environmental risk assessment and impact level

3.3 Climate Resilience Assessment

Using two petrophysical parameters (avg. Ø and Vsh), we conducted a detailed climate resilience assessment. Some observations were made in the various reservoirs, and their primary impacts were ascertained at the end of each evaluation. Reservoir B has an average. Ø (31%) indicated some possible pore pressure buildup, which could lead to sand destabilization and a high climate risk. However, with special monitoring and controlled reinjection, this could redistribute the pressure evenly and lessen the buildup of pressure along a section of the reservoir B. Observations from Reservoir C indicated possible fracturing of shaly layers under pressure due to cyclic loading and have a moderate climate risk. This primary impact can be mitigated through reinforced wellbores with eco-friendly casing. The evaluation of Reservoir A proved that high Vsh (2.0-6.5) resists pressure changes but may also crack; therefore, we can confidently say that this reservoir has a low climate risk. However, humidity-controlled drilling fluids could be used to mitigate problems that may arise during sequestration/storage in Reservoir A. The bubble plot in Fig. 5 showed the Kerri-Kerri Formation (Reservoir B) in a high-risk zone indicated with a red bubble, while the Gongila Formation is found in a low-climate risk zone (green bubble).

Table 3. Climate risk, impact assessment and mitigation strategies

Reservoir	Avg. Ø (%)	Avg. Vsh (API)	Climate Risk	Primary Impact	Mitigation Strategy
Kerri-Kerri (B)	31	1.3–5.1	High	Pore pressure buildup → sand destabilization	Pressure monitoring + controlled reinjection
Chad (C)	28.7	1.4–2.9	Moderate	Shale layers may fracture under cyclic loading	Reinforce wellbores with casing
Gongila (A)	22	2.0–6.5	Low	High Vsh resists pressure changes but may desiccate	Humidity-controlled drilling fluids

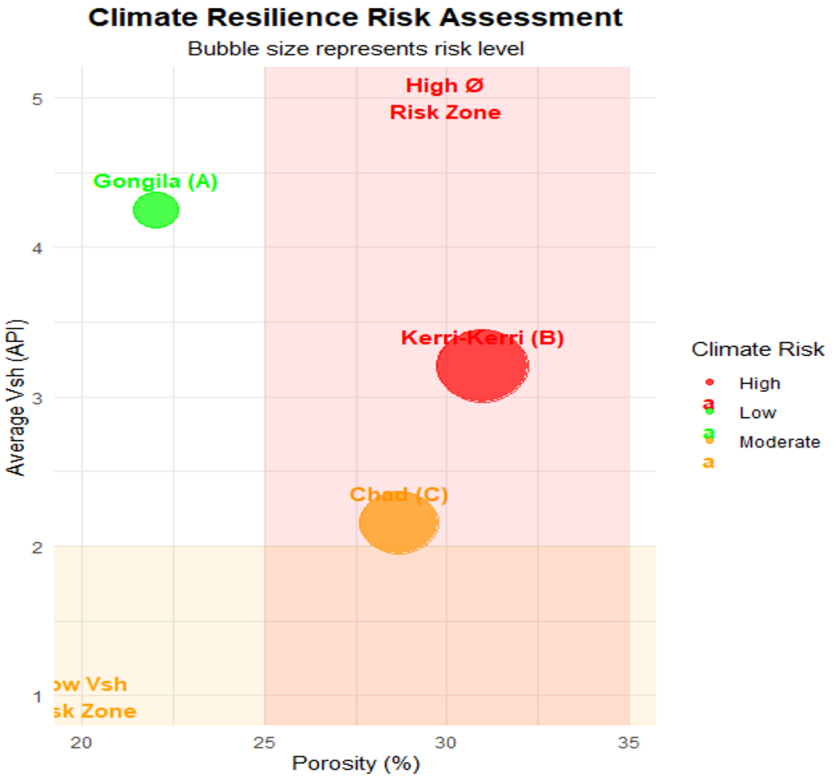

Fig. 5. Bubble plot showing climate resilience risk assessment

3.4 Repurposing Potential for Climate Mitigation

3.4.1 Carbon Capture and Storage (CCS)

CCS is a very essential aspect of modern environmental and climate change studies, an alternative means of storing CO_2 in subsurface reservoirs. The CO_2 storage potential assessment showed a distinct heterogeneity across the three formations. Our study revealed that the Kerri-Kerri Formation presents the best storage capacity (0.5–1.2 Mt CO_2/km²) due to its excellent porosity (31%), and an appreciable net thickness (230m). However, this

formation requires caprock analysis to ascertain the integrity of its sealing units across the Seloken field. Furthermore, we showed that the Chad Formation could arguably provide moderate storage capacity (0.3–0.6 Mt CO_2/km²) due to its very high porosity (28.7%) as shown in Table 4, and a net thickness of 80m.

From our well log analysis, we found that small shaly interbeds in the Chad Formation could reduce the injectivity during storage procedures. The Gongila Formation has limited potential (0.1–0.4 Mt CO_2/km²) due to lower porosity and higher shale content. Fig. 6 is a bar chart showing CO_2 storage potential and suitability by reservoir. Kerri-Kerri Formation ranked best among the three reservoirs, while the Gongila Formation was the least suitable.

Table 4. Petrophysical properties, storage capacity, and limitations

Reservoir	Avg. Ø (%)	Net Thickness (m)	Vsh (API)	Sw (%)	CO_2 Capacity (Mt/km²)	Key Limitation
Kerri-Kerri (B)	31.0	270–500	1.3–5.1	99.95	0.5–1.2	Requires caprock analysis
Chad (C)	28.7	120–200	1.4–2.9	96–100	0.3–0.6	Shaly interbeds reduce injectivity
Gongila (A)	22.0	60–400	2.0–6.5	96–100	0.1–0.4	High shale volume (Vsh)

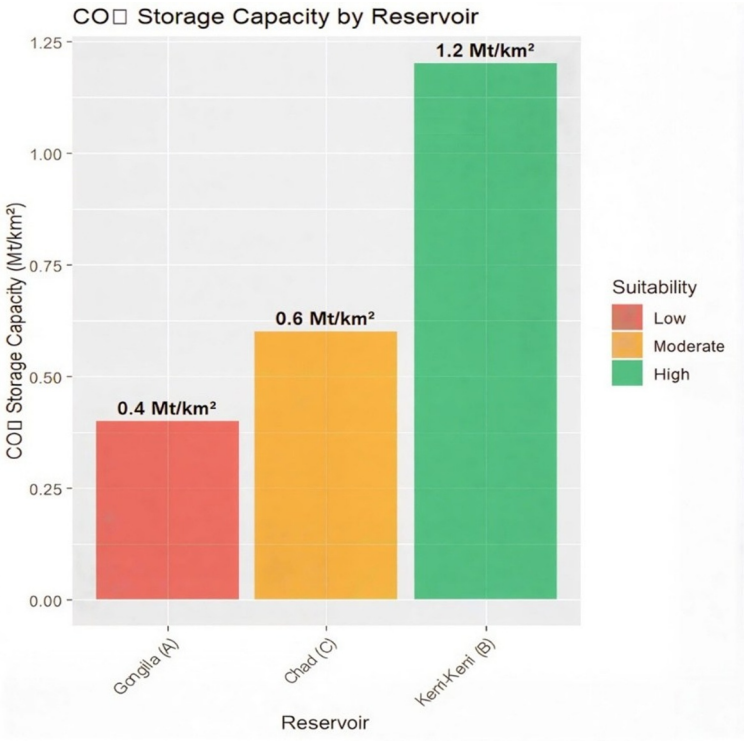

Fig. 6. Bar chart showing CO_2 storage capacity by reservoirs

A general seal integrity analysis performed using the Vsh at the top of each reservoir from the gamma ray log confirmed that formations with Vsh > 3.5 API (e.g., Herwa-1 in Gongila Formation with Vsh = 6.5 API) provide adequate containment for CO_2 storage, as shown in Fig. 7; those with Vsh < 3.5 require enhancement through technologies like Microbial-

Induced Calcite Precipitation (MICP). Table 5 shows the seal suitability for CCS of the Gongila Formation across the Bulte-1, Herwa-1, and Kadaru-1 wells.

Table 5. Seal integrity analysis for the Gongila Formation across three wells

Well	Reservoir	Avg. Vsh (API)	Vsh Classification	Seal Suitability for CCS
Bulte-1	A (Gongila)	3.4	Sandy shale	**Moderate** (near-seal threshold)
Herwa-1	A (Gongila)	6.5	Shaly sand	**Good** (Vsh >3.5)
Kadaru-1	A (Gongila)	2.0	Shaly sand	**Poor** (Vsh too low)

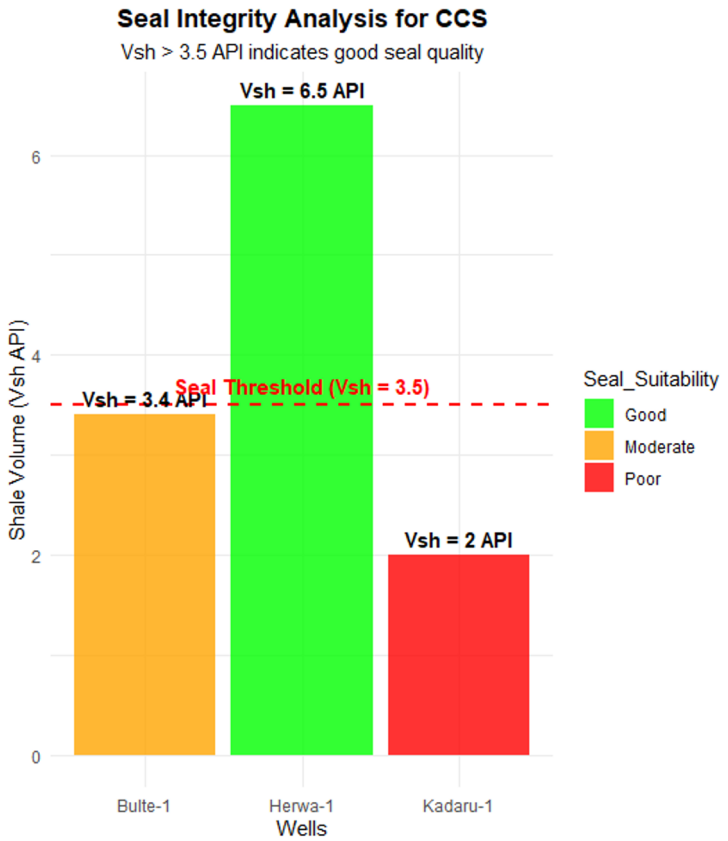

Fig. 7. Bar chart showing seal integrity analysis for CCS

3.4.2 Geothermal Energy Potential

The geothermal potential assessment identified promising opportunities, particularly in formations with high BVW (>0.25) and favorable temperature gradients. From our study, we observed that the Kerri-Kerri Formation can generate 1–2 MW/km², sufficient for rural electrification or district heating. However, implementation of binary cycle plants, successfully deployed in Russia's North Caucasus region, could optimize energy extraction from these low-enthalpy systems.

3.4.3 Aquifer Storage and Management

Reservoirs with moderate salinity and good porosity, such as the Chad Formation in Herwa-1 (Sw = 97.60%, Ø = 30%), offer potential for aquifer storage and managed recharge, supporting water resource sustainability in water-stressed regions. Table 6 presents potential environmental risks associated with various salinity levels. Our study showed that high salinity could be dangerous to groundwater if there are leaks across the sealing units, while low salinity simply indicates lower risk.

Table 6. Water Salinity Estimation from Resistivity logs and associated environmental risk

Well	Reservoir	Rt (Ωm)	Rw (Ωm)*	Sw (%)	Inferred Salinity	Environmental Risk
Kasade-1	B	20 (ILD)	0.1 (est.)	99.95%	**High salinity** (low Rt/Rw)	Risk to groundwater if leaked
Herwa-1	C	15 (ILD)	0.1 (est.)	97.60%	**Moderate salinity**	Potential aquifer contamination
Kadaru-1	A	50 (ILD)	0.1 (est.)	96.00%	**Low salinity** (high Rt)	Lower risk

3.5 Comparative Analysis: Nigeria-Russia Applications

The comparative analysis with Russian basins revealed significant synergies (Table 5). While Russian reservoirs generally offer higher CO_2 storage capacity (1.0–2.5 Mt/km² in West Siberia vs. 0.1–1.2 Mt/km² in Nigeria), Nigerian formations exhibit superior porosity (22–31% vs. 18–28% in Russia), suggesting complementary strengths. Furthermore, the Russian Achimov Formation has an appreciable thickness of about 600m, which is greater than the Kerri-Kerri Formation; hence it could potentially store more CO_2. Table 7 presents the disparity between the quality of the sealing units of the Seloken field (Vsh = 3.4–6.5) and the West Siberian Basin (Vsh = 7.0–9.0). Having compared the storage potentials for CCS in both basins, we made some suggestions regarding the synergy potential (see Table 8 and the bar charts in Fig. 8).

Table 7. Basin comparison and synergy potential

Parameter	Seloken Field, Chad Basin (Nigeria)	West Siberian Basin (Russia)	Synergy Potential
Avg. Porosity (Ø)	22–31% (Kerri-Kerri Formation)	18–25% (Uvat Group)	Nigerian expertise in high-Ø reservoir management
Net Thickness	120–500m (Kerri-Kerri Formation)	200–800m (Achimov Formation)	Russian experience with thick reservoir sequestration
Seal Quality	Vsh = 3.4–6.5 (Gongila)	Vsh = 7.0–9.0 (Bazhenov Shale)	Russian seal enhancement technologies applicable in Nigeria
CO_2 Capacity	0.1–1.2 Mt/km²	1.0–2.5 Mt/km²	Joint projects leveraging respective strengths

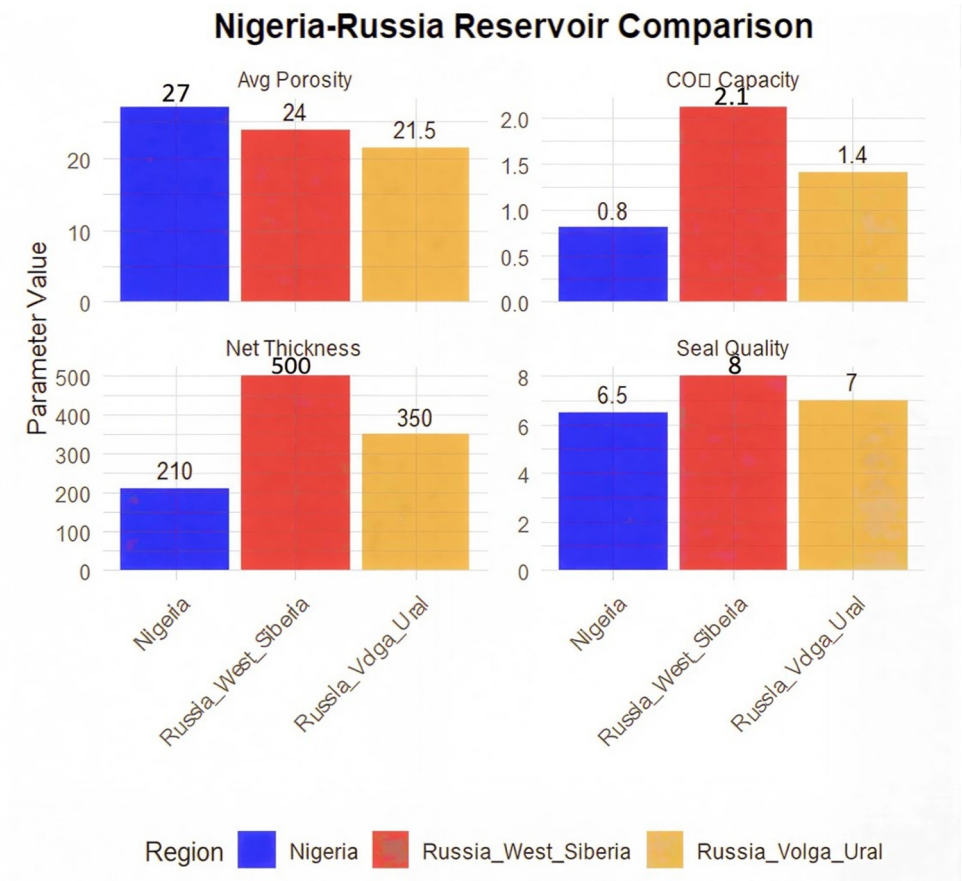

Fig. 8. Bar charts showing comparison of CO_2 storage parameters between Nigeria (Chad Basin) and Russia (West Siberia and Volga-Ural Basins)

Our comparative analysis identified three essential areas for collaboration:

I. **CCS Technology Transfer:** Russian expertise in seal enhancement in terms of adopting the polymer-enhanced caprocks, could address the sealing units challenges in predominant with the reservoirs of the Seloken field.

II. **Geothermal Development:** Adopting the Russian binary cycle plant technology (proven in low-heating systems) could maximize geothermal extraction from the high-Sw reservoirs of the study area (Chad Basin).

III. **Methane Mitigation:** The Seloken field aquifer management strategies could inform Russia's abandoned well protection approach, supporting Global Methane Pledge commitments.

3.6 Economic and Policy Implications

The economic analysis conducted in our study revealed that repurposing high-SW reservoirs for climate mitigation offers favourable economics compared to permanent abandonment, according to our various analyses. CCS implementation costs range from $500,000–1,200,000/km² with payback periods of about 5–10 years, while geothermal development costs range from $800,000–1,500,000/km² with similar payback periods.

Policy integration should focus on the following approaches:

I. Developing regulatory frameworks for reservoir repurposing

II. Establishing carbon credit mechanisms for aquifer-based CCS
III. Creating international standards for cross-border technology transfer
IV. Implementing monitoring, reporting, and verification (MRV) protocols

3.7 Transferable CO_2 Reduction Potential strategies from Russian Regions to our Study Area

It is essential to understand that our study is an assessment of petrophysical properties of high-SW reservoirs, which we showed can be repurposed for CCS. Alternatively, since there may be uncertainties regarding the effectiveness of our methods, until proven, we recommend CO_2 emission reduction strategies in Table 8 for four (4) cities in the Russian Federation and their associated feasibility (Low to high). Furthermore, adopting technologies such as MICP could easily enhance sealing units, especially in depleted reservoirs in regions around the globe where abandoned wells exist. Fig. 9 shows that Ufa has the best CO_2 emission reduction potential, while Kaluga has the least.

Table 8. CO_2 Emission Reduction Strategies for Russian Regions

Region	Key Emission Source	Proposed Mitigation	Technology	CO_2 Reduction Potential (kg/month/capita)	Feasibility
Moscow	Automobiles (460 kg)	Hydrogen fuel from saline aquifers	EM-47 mapped H_2 storage	50–100 (per EV user)	High
St. Petersburg	Gas heating (200 kg)	Geothermal district heating	Binary cycle plants (1.5 MW/km²)	200–256	Moderate
Ufa	Gas + Automobiles (610 kg)	CCS in depleted reservoirs	MICP-enhanced seals	214 (gas) + 50 (transport)	High
Kaluga	Electricity (85 kg)	Solar-wind hybrid + grid storage	Battery storage + PV/Wind	60–85	Low

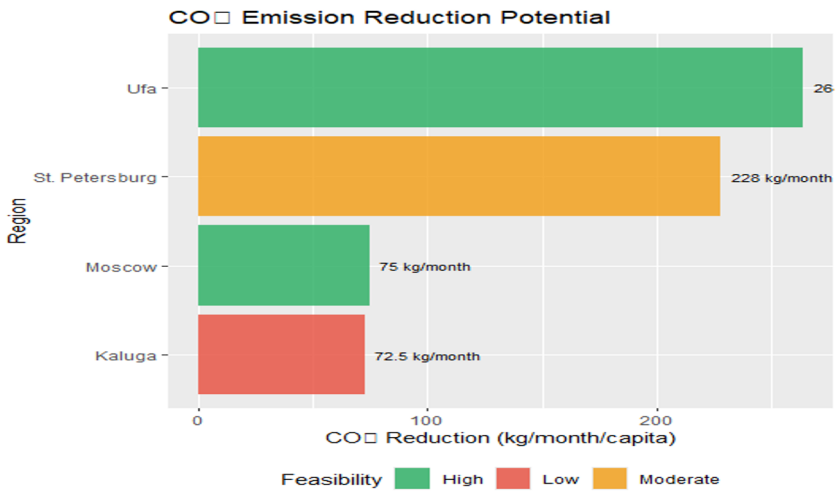

Fig. 9. Bar chart showing the CO2 emission reduction potential across some Russian cities

4 Climate Adaptation: Lessons from Russia

Climate adaptation involves the potential challenges associated with CCS in the study area. Furthermore, to ensure proper adaptation strategies, Russian solutions as proposed in Table 10 can be applied to the Seloken field. From Three major challenges, such as thin seals, low-temperature geothermal, and saline aquifers, were identified through well log analysis with the available dataset. Our study identified some solutions, such as polymer-enhanced caprock and electro-dialysis; however, it remains to be seen how feasible these solutions would be.

Table 9. Policy and Technology Transfer

Challenge	Russian Solution	Applicability to Seloken
Thin Seals	Polymer-enhanced caprocks (Gazprom)	Feasible but costly
Low-T Geothermal	Binary cycle plants (Kamchatka)	Viable for rural electrification
Saline Aquifers	Electro-dialysis (Rosatom)	High CAPEX; prioritize monitoring

5 Conclusion and Recommendations

This study demonstrates that water-saturated reservoirs, traditionally considered economic liabilities, represent significant opportunities for climate change mitigation and sustainable resource management. The integrated petrophysical and climate resilience framework provides a comprehensive approach for assessing environmental risks while identifying repurposing potential. Environmental risks in high-Sw reservoirs are quantifiable and manageable through systematic petrophysical monitoring, with specific thresholds ($Rt < 25$ Ωm, $Ø > 25\%$, $Vsh < 3.5$) indicating elevated risk levels. Our study from the Seloken field indicates repurposing potential is substantial, with CO_2 storage capacities of 0.1–1.2 Mt/km² and geothermal potential of 1–2 MW/km², transforming environmental liabilities into climate assets. Cross-continental applications offer accelerated decarbonization pathways, with Chad Basin reservoir management approaches informing Russian GHG reduction strategies, and Russian CCS technologies enhancing the seal integrity of caprocks in the Seloken field. Climate resilience varies significantly by reservoir characteristics, necessitating formation-specific adaptation strategies that account for porosity, shale volume, and hydrological conditions. Adopting CCS in high-SW reservoirs will not only reduce GHG emissions (gas flaring) but also provide an avenue platform for oil and gas companies to maximise brownfields rather than abandon them and optimise wells for gas storage in an eco-friendly manner, promoting sustainable development. We recommend the implementation of continuous resistivity monitoring in high-risk zones to prevent groundwater contamination, application of MICP and polymer-enhanced seal technologies to improve containment integrity, deployment of binary cycle plants for optimized geothermal energy extraction, establishment of baseline characterization and ongoing monitoring protocols, development of regulatory frameworks for reservoir repurposing and cross-border technology transfer, integration of water-saturated reservoir management into national climate action plans, creation of carbon credit mechanisms for aquifer-based CCS projects, and formation of international standards for MRV of stored CO_2. Finally, it is essential to conduct pilot-scale testing of repurposing technologies, investigate long-term fluid-rock interactions in CO_2-brine systems, develop advanced monitoring techniques for leak detection, and explore hybrid systems combining CCS with geothermal energy extraction.

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