



# Resource Extraction and Regional Sustainability: An Economic Perspective on Water-Rock Interactions in Oil-Rich Areas

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## ABSTRACT

Water-rock interactions play a critical role in shaping the geochemical and geomechanical characteristics of subsurface formations in oil-rich regions. Resource extraction in oil-rich regions significantly disrupts hydrogeological systems, particularly through water-rock interactions that affect long-term regional sustainability. The research adopts an economic perspective to assess the impact of oil extraction on subsurface geochemistry, focusing on the economic valuation of water degradation due to mineral dissolution, salinity shifts, and mobilization of trace elements. The operation is carried out using IBM SPSS software version 27.0, where multivariate regression analysis and t-tests are used to statistically model the relationship between extraction intensity, groundwater chemistry, and socio-economic outcomes across major oil-producing regions. The analysis incorporates time-series data on water quality indices, oil output, and regional economic indicators such as agricultural productivity loss, healthcare costs, and water treatment expenditures. Findings show a statistically significant correlation ( $p < 0.01$ ) between increased extraction rates and elevated concentrations of sodium, chloride, and heavy metals in local aquifers. In high extraction zones, the average agricultural productivity is 2.34 tons/ha, while in low extraction zones it is 2.91 tons/ha ( $t = -4.73$ ,  $df = 98$ ,  $p < 0.001$ ). Public health expenditure in high extraction areas averaged \$124.7 USD/capita, compared to \$89.3 USD/capita in low extraction areas ( $t = 5.16$ ,  $df = 98$ ,  $p < 0.001$ ). The research defines regional sustainability as the balance between environmental protection, economic resilience, and social well-being in oil-rich areas, assessing groundwater degradation, economic losses, and community impact caused by water-rock interactions linked to oil extraction activities.

## KEYWORDS

Water-Rock Interactions, Oil Extraction, Regional Sustainability, Cost-Benefit Analysis, Agricultural Loss, Economic.

## 1. INTRODUCTION

Rock is a normal geological material in nature, consisting of rigid mineral crystal grains with many inter-connected cracks that transmit the fluids. The interaction of the rock and crack fluid water leads to rock failure [1]. Water-rock interaction (WRI) refers to unique changes in the chemistry of groundwater due to its interaction with the host rock. The significant interaction between the groundwater and the surrounding rock formation generates new minerals with different stability-dynamic properties and hydro chemical composition. Mechanisms of interaction generate aqueous components in the aquifer with different levels of dissolved elements, which impact groundwater quality, especially in arid system zones. [2].

Toxic substances are delivered into soil and water in high concentrations due to WRI. Toxic trace elements enter and remain in the environment and continue to be adsorbed and accumulate in soils and water or in different phases through geochemical processes. However, the variable geochemical behavior of elements causes changes in water geochemistry during WRI processes [3]. The WRI process regulates the alteration of physical and chemical-mineralogical changes of all types of rock, which leads to dissolved components being released into groundwater. The concentrations of solutes in the groundwaters are influenced by the chemical characteristics of the geological setting, original rainwater, and the amount of the WRI process, which connects with the dwelling time in the aquifer method [4].

The changes in geomechanical properties due to WRI are associated with the formation of microcracks resulting from the dissolution of the internal stresses and mineral components. As a result of the WRI, the internal stress arises from the micro deformation that is typically caused by the swelling of the clay minerals in the shale rocks and sandstones. Micro-cracks begin as a result of the changed stress, if the stress conditions meet the criteria for failure of the rock [5]. The influence of WRI on rock properties becomes particularly significant when rainwater infiltrates the rock mass. These interactions affect both the rock's geochemical composition and mechanical integrity. Dynamic WRI accelerates the softening process and makes rocks more vulnerable to weathering and cracking [6]. WRI in natural environments is highly complicated and changeable, making it difficult to fully duplicate all influencing factors in laboratory settings [7].

WRI has a critical impact on the geochemical and geomechanical properties of subsurface formations in oil-rich areas. Resource extraction in oil-rich areas distinctly alters the hydrogeological system, particularly through WRI, which affects long-term regional sustainability. The research examines oil extraction impacts on subsurface geo chemistry from an economic perspective; specifically, it considers the economic loss of water quality due to mineral dissolution, salinity impacts, and trace element mobilization. The research is useful for environmental policymakers, resource managers, and public health professionals in establishing a balance between oil extraction and regional sustainability.

The organization of the research contains subsections such as Section 1, which covers the introduction of the research. Section 2 discusses the related work. The material and methods used to assess the impact of oil extraction on subsurface geochemistry were presented in Section 3. Section 4 represents the outcomes of the research and discusses the outcomes in detail. Section 5 concludes the research.

## **2. RELATED WORK**

The groundwater, based on chemical ions and heavy metal characteristics, was classified using established analytical methods and Hierarchical Cluster Analysis [8]. The findings revealed four clusters in the dry season and five clusters in the wet season, demonstrating seasonal change in contamination. However useful for environmental planning, limitations included the use of spatially constrained samples and seasonal data variability. The WRI was examined [9] during CO<sub>2</sub> injection impact on shale reservoir parameters. Static and dynamic core experiments showed that CO<sub>2</sub>-induced reactions affect porosity and permeability through mineral formation, pore clogging, and fracture production. The results varied according to PV number, pressure, and temperature. Scale limits and controlled lab settings did not fully replicate field dynamics.

The trace element behavior in co-produced waters was investigated from several hydrocarbon basins in the United States using USGS data and shale leaching experiments [10]. The methods involved comparing 26 element concentrations in generated waters and leachates with varied pH and ionic strength. The results revealed partial replication of trace elements but not Li, Sr, or Ba. Limitations included laboratory dilution effects that obscure natural interactions. The spatial analysis was used to analyze groundwater quality throughout 23 Mandals in the Nellore area [11]. Using IRS P6 LISS-III satellite data, geological maps, and chemical data from 57 wells, inverse distance weighted

interpolation in ArcGIS was performed. The results revealed geogenic pollution from rock-water interaction, particularly after the monsoon. Limitations included reliance on data and a restricted number of wells.

The oil-WRI was investigated to increase oil recovery by assessing oil sand wettability with the polar diluters and surfactants utilizing the enhanced Washburn method and the OWRK model [12]. The results suggested that HABS and PS surfactants minimize adhesion and increase oil stripping efficiency. However, crude oil has lower wetting rates. Limitations included laboratory circumstances that did not fully simulate complex in-situ reservoir ecosystems. The WRI involving heavy metal migration and pH changes in groundwater, as it interacts with oil shale and ash was examined [13]. Pb, Cr, and Zn concentrations were evaluated using step-by-step tests and PHREEQC geochemical simulations at various CO<sub>2</sub> pressures and temperatures. The results revealed pH shifts and temperature-dependent metal content differences, with greater Pb concentrations in ash solutions. Limitations include laboratory conditions that do not reflect all of the in-situ complications.

The changes in permeability and porosity in the unconsolidated sandstone heavy oil reservoirs after CO<sub>2</sub>+steam+AOS and CO<sub>2</sub>+steam injection were investigated [14]. Results from static monomineral reactions and dynamic sand pack experiments demonstrated that AOS reduced mineral dissolution and provided more stable permeability. However, laboratory circumstances have failed to adequately recreate complicated field-scale reservoir processes and long-term impacts. The oil recovery was improved [15] by investigating the effects of brine salinity and silica nanoparticles on Interfacial Tension (IFT) and wettability in carbonate reservoirs. Magnesium chloride at 1 M significantly reduced IFT and wettability, according to contact angle measurements. However, silica nanoparticles had little effect, and laboratory conditions do not exactly simulate reservoir conditions. The sedimentary evolution and lithofacies of the Gulong Shale in northeastern China to evaluate shale oil enrichment were examined [16]. The results obtained by paleolake-level reconstruction and lithofacies analysis, demonstrated the impact of lithofacies on reservoir performance and oil movability. Limitations included region-specific findings that are not immediately transferable to other non-marine shale formations without additional validation.

### **3. MATERIALS AND METHODS**

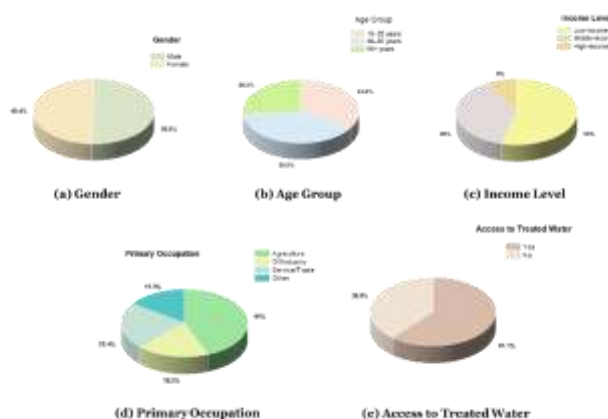
The research examines oil extraction impacts on subsurface geochemistry from an economic perspective, it considers the economic loss of water quality due to mineral dissolution, salinity impacts, and trace element mobilization. This section describes the systematic approach used in assessing the environmental and economic impacts of oil extraction through water-rock processes. By integrating spatio-temporal patterns in groundwater chemistry with socio-economic data, the research applies statistical methods to identify commonalities. The chosen perspective, methodology, and analysis ensures a dependable, verifiable analysis that is useful for evidence-based policy.

#### **3.1. Data Collection**

The research examined a total of 12,800 respondents in essential oil-producing regions recognized for heavy resource extraction activities. The respondents included local farmers, healthcare officials, and water management authorities, representing diverse socio-economic backgrounds. The demographic data included factors such as age groups, income levels, and occupations, enabling a comprehensive assessment of the economic and social influences related to WRI and resource extraction. Table 1 represents the demographic features of the respondents in oil-rich regions. The graphical representation of the demographic features of respondents in oil-rich regions is presented in Figure 1.

**Table 1: Demographic Features of the Respondents in Oil-Rich Regions**

Variable	Category / Description	N=12,800	N (%)
Gender	Male	6,480	50.6%
	Female	6,320	49.4%
Age Group	18–35 years	4,320	33.8%
	36–55 years	5,110	39.9%
	56+ years	3,370	26.3%
Income Level	Low-income (<\$5,000/year)	6,910	54.0%
	Middle-income (\$5,001–\$15,000/year)	4,870	38.0%
	High-income (>\$15,000/year)	1,020	8.0%
Primary Occupation	Agriculture	5,630	44.0%
	Oil Industry	2,340	18.3%
	Service/Trade	2,870	22.4%
	Other	1,960	15.3%
Access to Treated Water	Yes	7,820	61.1%
	No	4,980	38.9%



**Figure 1: Visual representation of Demographic Features of the Respondents in Oil-Rich Regions**

Table 1 shows the demographics of 12,800 people surveyed in oil-rich regions, with a roughly equal gender distribution of 49.4% female and 50.6% male. The majority (39.9%) are between the ages of 36 and 55, while 26.3% are aged 56 and above, and 33.8% were in the 18–35 age group, and more than half (54.0%) have a low income of less than \$5,000 each year. Agriculture is the primary occupation of 44.0% of respondents, followed by service/trade (22.4%) and the oil sector (18.3%), while 15.3% are engaged in other occupations. 61.1% of the population has access to treated water, while 38.9% have no access, revealing gaps in basic services.

### **3.2. Selection criteria**

The gathered participants were divided into two criteria, such as inclusion criteria and exclusion criteria. Participants aged 18 and above from oil-producing locations with established WRI impacts were included (n = 12,800). Individuals with active involvement in agriculture, local governance, public health, or water management were chosen to ensure relevant socioeconomic insights. Participants under 18 years old, non-residents of oil extraction zones, and individuals avoiding to offer informed consent were eliminated (n = 645).

### **3.3. Research Method**

A quantitative method was adopted to assess the link between extraction intensity and changes in groundwater and economic outcomes. The research employs principles of environmental economics to measure how oil extraction activities contribute to water quality deterioration and the related downstream economic effects. The objective is to measure the fixed and interrelated dependencies in these factors to provide evidence related to future planning and policies for managing environmental quality and social costs of oil extraction in remote communities.

### **3.4. Statistical Analysis**

The data was analyzed using IBM SPSS version 27.0, where Multivariate Regression Analysis (MRA), Pearson Correlation Analysis and paired sample t-tests are used to statistically model the relationship between extraction intensity, groundwater chemistry, and socio-economic outcomes across major oil-producing regions. Groundwater quality data were collected using standardized laboratory tools during regional hydrological surveys, and economic indicators were derived from government and institutional databases. These instruments are utilized in such a manner that ensures accurate measurement and comprehensive research of environmental and economic factors. MRA was applied to explore the association between the oil extraction and contamination of groundwater, and the subsequent economic costs. Independent t-tests were used to determine the statistical significance of the changes reported at different extraction levels. Pearson correlation analysis is used to assess the degree of relationship with regard to oil extraction intensity to changes in groundwater quality indicators such as sodium and heavy metals. Analyses were performed at a 95% confidence level and a p-value cutoff of  $< 0.05$ . Strong connections were identified at  $p < 0.01$ .

## **4. RESULT AND DISCUSSION**

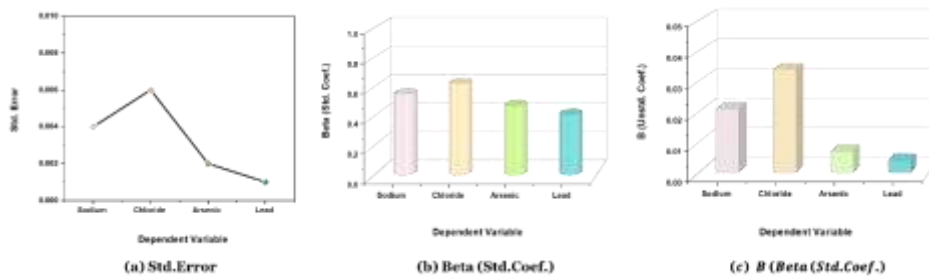
The research adopts an economic approach to assess the influence of oil extraction on subsurface geochemistry, with a particular emphasis on the economic value of water deterioration caused by mineral dissolution, salinity fluctuations, and trace element mobilization. The research used Multivariate Regression, Independent samples t-test and person correlation analysis to assess the influence of oil extraction on surface geochemistry.

### **4.1. Evaluation of Groundwater Quality Degradation via Multivariate Regression Analysis (MRA)**

MRA is a statistical method that assesses the association between the numerous independent variables and one dependent variable at the same time. It helps to quantify the impact of oil extraction intensity on various groundwater quality parameters and socioeconomic impacts. The research provides an evidence-based assessment of environmental degradation and its larger regional economic effects. Table 2 displays the outcomes of an MRA to determine the impact of oil extraction on groundwater chemical components. Figure 2 represents the outcomes of the oil extraction impact on groundwater contaminants using MRA.

**Table 2:** Multivariate Regression Analysis of Oil Extraction Impact on Groundwater Contaminants

Dependent Variable	<i>B (Unstd. Coef.)</i>	<i>Std. Error</i>	<i>Beta (Std. Coef.)</i>	<i>t</i>	<i>p – value</i>
Sodium	0.021	0.004	0.55	5.25	< 0.001
Chloride	0.034	0.006	0.62	5.67	< 0.001
Arsenic	0.007	0.002	0.47	3.89	< 0.001
Lead	0.004	0.001	0.41	3.62	0.001
R-squared (R <sup>2</sup> )	-	-	-		0.67
F-statistic	-	-	-		38.4 (p < 0.001)



**Figure 2:** Outcomes of the Oil Extraction Impact on Groundwater Contaminants using MRA

The quantities of sodium ( $B = 0.021, p < 0.001$ ), arsenic ( $B = 0.007, p < 0.001$ ), chloride ( $B = 0.034, p < 0.001$ ) and lead ( $B = 0.004, p = 0.001$ ) were significantly correlated with extraction intensity, indicating that higher extraction levels resulted in higher amounts of contaminants. The model demonstrates statistical significance ( $F = 38.4, p < 0.001$ ) and the capacity to explain 67% of groundwater chemistry variance ( $R^2 = 0.67$ ) provides evidence for how extraction operations strongly influence the quality of subsurface water.

#### 4.2. Statistical Evaluation of Environmental and Economic Differences across Extraction Zones using the Independent Samples t-Test

Independent Sample t-test analysis is a statistical method that associates the means of the two independent groups to observe that there is a significant difference. It helps to compare differences in groundwater quality and socioeconomic factors between regions with high and low oil extraction intensities. The research determines if the observed variations are statistically significant and relevant. Table 3 shows statistically significant differences between high and low extraction zones across key water quality and economic indicators.

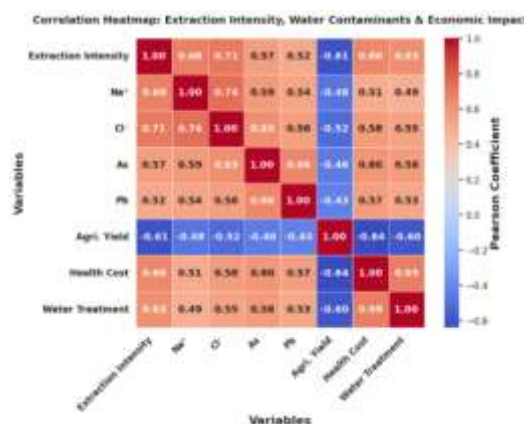
**Table 3:** Independent Samples t-Test – Groundwater Chemistry and Socio-Economic Impact by Extraction Zone

Water Quality Parameter and Economic Indicator	High Extraction Mean	Low Extraction Mean	<i>t</i>	<i>df</i>	<i>p</i> – value
Total Dissolved Solids	847.3	602.1	4.91	98	< 0.001
pH	6.71	7.12	-2.43	98	0.017
Electrical Conductivity	2124.5	1453.6	4.36	98	< 0.001
Agricultural Productivity	2.34	2.91	-4.73	98	< 0.001
Public Health Expenditure	124.7	89.3	5.16	98	< 0.001
Water Treatment Cost	48.2	32.6	4.88	98	< 0.001
Agricultural Income Loss (%)	17.4%	3.2%	5.67	98	< 0.001
Disease Prevalence	87.2	54.1	4.12	98	< 0.001

High extraction zones have higher Total Dissolved Solids (847.3 vs 602.1), electrical conductivity (2124.5 vs 1453.6), and a lower pH (6.71 vs 7.12), which all indicate water quality has regressed ( $p < 0.05$ ). Consequently, these extractive areas showed lower agricultural productivity, (2.34 vs. 2.91 tons per hectare) as well as higher public health expenditure (124.7 vs. 89.3), higher water treatment costs (48.2 vs. 32.6), higher agricultural income loss (17.4% vs 3.2%), and higher disease incidence (87.2 vs 54.1 per 1000).

### 4.3. Evaluation of Groundwater and Economic Indicators Using Pearson Correlation Analysis

Pearson Correlation Analysis assesses the size and direction of a linear association between two continuous variables. It is used to assess the degree of relationship with regard to oil extraction intensity to changes in groundwater quality indicators such as sodium and heavy metals. This helps in determining which environmental and economic factors are most closely related, providing early evidence of correlation for the regression analysis. Figure 3 represents the evaluation of the correlation between extraction intensity and groundwater sodium concentration using Pearson Correlation Analysis.



**Figure 3:** Evaluation of the correlation between extraction intensity and groundwater sodium concentration using Pearson Correlation Analysis

Figure 3 shows substantial correlations ( $p < 0.01$ ) between extraction intensity and numerous geochemical and economic parameters. Notably, extraction intensity has a strong positive correlation with sodium ( $r = 0.68$ ), lead ( $r = 0.52$ ), arsenic ( $r = 0.57$ ), and chloride ( $r = 0.71$ ) concentrations, demonstrating that higher extraction results in more contamination. Concurrently, negative correlations are observed between extraction intensity and agricultural yield ( $r = -0.61$ ), implying lower productivity as water quality deteriorates. Strong positive correlations are also shown between extraction intensity and both public health costs ( $r = 0.66$ ) and water treatment expenses ( $r = 0.63$ ), emphasizing the socioeconomic impact of environmental degradation.

There were limitations in terms of spatially limited samples and seasonal variability of the data [8], as well as scale limitations and the inability to fully mimic field dynamics [9]. Laboratory dilution effects may have altered the natural WRI [10], and the analysis was further complicated by dependence on secondary data and a limited number of monitoring wells [11]. The results of the research showed evidence of increased oil extraction intensity, which significantly increases groundwater quality, with increasing conditions of sodium, chloride, arsenic, and lead, through the use of multivariate analysis. The independent t-tests showed that high extraction zones have worse water quality, a decrease in agricultural productivity, and greater health and treatment costs. This Pearson correlation highlighted the significant relationships between extraction and the environmental and economic consequences of extraction. These results reinforced the need for sustainable extraction strategies and practices to preserve natural ecological integrity and regional socioeconomic health.

## 5. CONCLUSION

The research assessed the impact of oil extraction on subsurface geochemistry from an economic perspective, focusing on the economic valuation of water degradation caused by mineral dissolution, salinity shifts, and the mobilization of trace elements. The research demonstrated that oil extraction activities in resource-rich regions had a significant impact on subsurface water quality through intensified WRI. Elevated levels of sodium, chloride, and heavy metals were found to be strongly correlated with increased extraction intensity, as confirmed by MRA and Pearson correlation analyses. These geochemical alterations were shown to have quantifiable economic effects, such as diminished agricultural production and greater medical and water treatment costs. Low-income and marginalized communities incurred much higher economic costs, highlighting the social inequities related to environmental degradation. By integrating hydrogeological and economic data, the research quantified unexamined costs of extraction, and recommended sustainable resource management practices that balance environmental production, economic sustainability, and social equity in oil-producing areas. The research findings indicated that augmented oil extraction intensity resulted in a strong relationships with sodium ( $r = 0.68$ ), chloride ( $r = 0.71$ ) and lead ( $r = 0.52$ ) in groundwater. In high extraction zones, the average agricultural productivity is 2.34 tons/ha, while in low extraction zones it is 2.91 tons/ha ( $t = -4.73$ ,  $df = 98$ ,  $p < 0.001$ ). Public health expenditure in high extraction areas averaged \$124.7 USD/capita, compared to \$89.3 USD/capita in low extraction areas ( $t = 5.16$ ,  $df = 98$ ,  $p < 0.001$ ). Limitations include data availability and regional variability, and future research needs to concentrate on long-term monitoring and advanced mitigation measures for sustainable resource management.

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