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Understanding Sustainability Through Socio-Ecological Trade-Offs: Field Evidence of Traditional Oil Mining and Groundwater Quality Toward the SDGs

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Abstract: This study explores human-nature relationships through a socio-ecological perspective, focusing on traditional oil mining in Wonocolo, Indonesia, widely known as “Little Texas”. The analysis was conducted through field observations, in-depth interviews with 40 local stakeholders, and laboratory analysis of 40 groundwater samples collected from community dug wells. Results show residents rely on dug wells, piped-water, and artesian springs, with significant seasonal scarcity. Water quality assessment indicates that most physical parameters remain within acceptable limits (pH 6.40–8.00; electrical conductivity 0.43–2.26 mS/cm; temperature 22.00–31.00 °C). However, localized elevations in electrical conductivity at several sampling points suggest potential hydrochemical alterations in the shallow aquifer that may be associated with traditional oil extraction activities, particularly in a karst-dominated landscape. Although direct measurements of TPH and Oil & Grease were not available for a comprehensive ecotoxicological assessment, these findings highlight a critical socio-ecological trade-off in which short-term economic benefits from oil production may increasingly pressure long-term groundwater security. The study concludes that managing these interdependencies requires participatory governance and waste-stream regulation tailored to the karst landscape. Integrated policies are essential to ensure that economic benefits do not undermine the community's fundamental access to clean water, aligning with SDG 6 and SDG 12.

Keywords: Ecosystem services; ES trade-offs; Human-nature interaction; Traditional oil mining

Introduction

Human geography plays a crucial role in examining how humans interact with their environment. This relationship between humans and nature constitutes a fundamental aspect of sustaining life on Earth, encompassing both human dependence on natural resources to meet daily needs and the responsibility to maintain their long-term sustainability (Berkes & Folke, 1998; Cai et al., 2024; Mouysset, 2023).

However, historical evidence often reveals an imbalanced trajectory in which overexploitation—driven by population growth and economic expansion—leads to significant ecosystem degradation (Foley et al., 2005). This imbalance has become increasingly critical as the global community strives to achieve the Sustainable Development Goals (SDGs), particularly in balancing economic growth with environmental preservation. The concept of Socio-Ecological Systems (SES) offers such a framework by emphasizing interdependencies and

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feedback loops between social and ecological components that underpin long-term system resilience (Ostrom, 2009).

A compelling case reflecting this tension is traditional oil mining in Wonocolo, Bojonegoro, East Java, widely known as "Little Texas." In this region, community-based oil extraction has been practiced for generations using traditional technologies (Rahaditya & Dariyo, 2020, 2021). These mining activities are known to have contributed positively to the local economy by creating employment opportunities and improving community welfare (Puspitasari & Sugiyanto, 2018). At the same time, they impose considerable ecological pressures. In the absence of adequate management, traditional oil extraction poses risks of soil and groundwater contamination, greenhouse gas emissions, and disruption of terrestrial biodiversity (Siregar et al., 2019; Taufik et al., 2020; Nasution & Fitria, 2023). In particular, the discharge of drilling waste and saline produced water raises concerns regarding the vulnerability of shallow groundwater systems, especially within karst landscapes characterized by high permeability and rapid subsurface water movement. Given the strong dependence of local communities on shallow groundwater for daily use, clean water security emerges as a critical and underexplored issue in the Wonocolo oil field.

Beyond environmental degradation, traditional oil mining presents a complex socio-economic dilemma. Socially, uneven profit distribution and conflicts of interest among stakeholders may increase inequality within the community (Puspitasari & Sugiyanto, 2018). Economically, although traditional oil mining remains a primary livelihood for many households, the heavy reliance on depletable resources poses long-term risks to economic sustainability and local resilience. This case is particularly relevant in the context of increasing global energy demand and the growing urgency of climate change mitigation (Rockström et al., 2009; Taufik et al., 2020). These conditions highlight the need to better understand how economic benefits derived from resource extraction interact with environmental limits and social well-being.

This study aims to examine human–environment relationships in Wonocolo through a socio-ecological perspective. By analyzing ecosystem trade-offs associated with traditional oil mining, this research provides a problem-based assessment of resource management strategies that seek to balance short-term economic benefits with the long-term provision of clean water. Integrating qualitative insights from local communities with empirical groundwater observations, this study contributes to a more comprehensive understanding of resource governance in small-scale extractive settings. Ultimately, the findings are expected to inform context-sensitive management approaches and contribute to broader discussions related to the 2030 Agenda for Sustainable Development, particularly in relation to SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production).

Method

Studi Area

The study was carried out in Wonocolo, Kedewan Sub-district, Bojonegoro Regency, East Java, Indonesia. Wonocolo located in the northern part of East Java's interior zone, approximately 60 km southwest of Bojonegoro town. It is recognized as one of Indonesia's main centers for traditional oil mining, well-known as "Little Texas" (Pemkab Bojonegoro, 2016). This activity has been passed down through generations (Puspitasari & Sugiyanto, 2018). This unique combination of geological resources, makes Wonocolo become an ideal location for examining trade-offs between ecosystem services and socio-ecological resilience (Daily et al., 2009).

Data Collection

Ecosystem trade-off in this study was assessed by using household water quality. Key parameter that used in water quality was salinity, electrical conductivity, pH, and temperature (WHO, 2017). As a primary data, this data was collected from 40 respondent by interview and observation using a random sampling. To enhance the information, this study also using secondary data from remote sensing and GIS to reflect spatial aspect. Spatial data used in this study comes from DEMNAS (National Digital Elevation Model), accessed through Ina-Geoportal, available through http://tanahair.indonesia.go.id/ and can be downloaded depending on the study area. DEMNAS has a spatial resolution of 0.27 arc-seconds, which is equivalent to approximately 8.25 meters at the equator. This resolution allows for sufficiently detailed topographic representation for spatial analysis at regional to medium-local scales. This approach enabled a comprehensive analysis of the relationship between socioeconomic characteristics, traditional oil mining activities, and water quality conditions (Goodchild, 2010) in the Wonocolo area. Secondary data used in this study can be seen in Table 1.

Table 1. Secondary Data Source of this Study

Input	Description
DEMNAS	Elevation model of Wonocolo
LULC.tif	Land use/land cover raster
Watershed.shp	Watershed/subcatchments
wonocolo_points.geojson	Groundwater points

Data Analysis

Data analysis in this study was conducted using two main approaches. First, a study of the socioeconomic characteristics of the community was conducted to understand the living conditions of residents around traditional oil mining areas (Scoones, 1998). Aspects such as livelihoods, water consumption patterns, the level of dependence on natural resources, and the economic impact of mining activities were the main focus of this analysis. This approach provides a comprehensive picture of how community economic activities relate to environmental use and how socioeconomic factors influence patterns of human interaction with the surrounding ecosystem (Ostrom, 2009; Scoones, 1998).

Furthermore, water quality analysis was conducted using a quantitative descriptive approach by comparing field measurements with clean water quality standards as stipulated in Minister of Health Regulation No. 2 of 2023 (Rahayu et al., 2025; Shodiq & Setyono, 2025; Nadiro et al., 2023). This approach was used to assess the suitability of the water used by the community for their daily needs and to identify potential health risks that may arise from mining activities (WHO, 2017). Additionally, to gain a deeper understanding of the relationship between the community and its environment, a cultural ecology approach with a socio-ecological framework was used (Steward, 1955). This approach aimed to explore how local communities adapt to environmental challenges, including in terms of water resource management and adaptation strategies to changes in environmental quality due to environmental degradation (Berkes & Folke, 1998; Ostrom, 2009).

Table 2. Threshold and Parameter

Parameter	Threshold	References
pH	6.5 – 8.5	Permenkes (2010) and WHO (2017)
Conductivity	~ < 1500 µS/cm (≈ TDS < 1000 mg/L)	WHO (2017) and USEPA (2023)
Temperature	22–30 °C (tropic)	Boyd (2015) and WHO (2017)
Salinity	< 0.5 PSU	WHO (2017) and Davis & Cornwell (2012)

Flowchart

The flowchart illustrates the sequential stages of the research process examining socio-ecological trade-offs in Wonocolo. The study begins with field observations, stakeholder interviews, groundwater sampling, and secondary data collection. These data are analyzed through socio-economic assessment, groundwater quality evaluation, and spatial (GIS) analysis (Santikanuri et al., 2025). The results are then integrated to assess the trade-off between oil exploitation and groundwater quality. Finally, the study formulates conclusions and recommendations, highlighting implications for sustainable development goals.

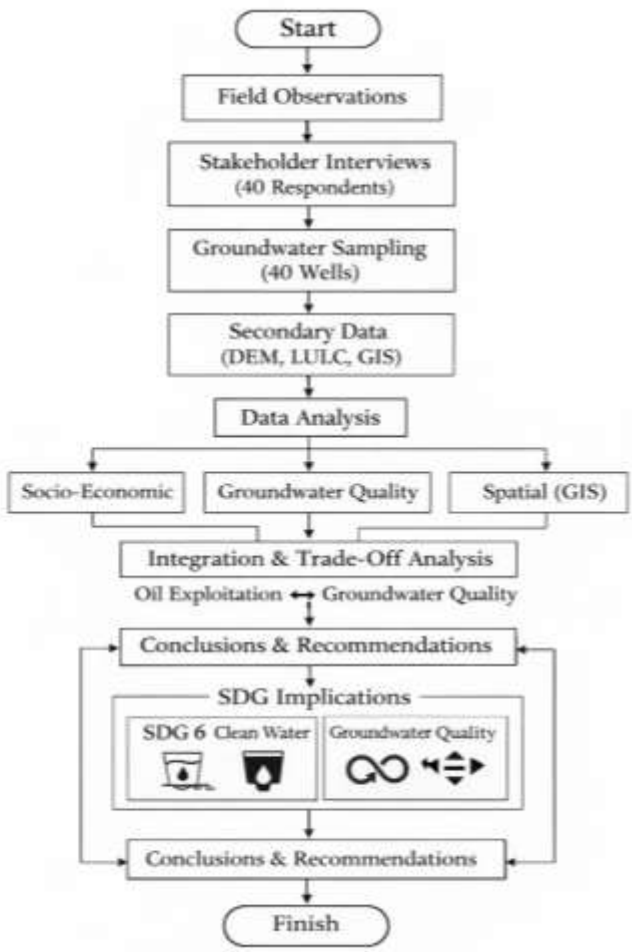

Figure 1. Research Flowchart

Result and Discussion

All relationships within social–ecological systems (SES) are fundamentally driven by various aspects of biodiversity, which underpins the structure and functioning of ecosystems (Balvanera et al., 2014; Berkes & Folke, 1998). Biodiversity shapes the complexity, resilience, and productivity of ecological processes that sustain human well-being. Therefore, analysing these interactions is essential to design effective biodiversity conservation and management strategies. The creation of ecosystem services (ES) emerges from highly complex networks of ecological interactions characterized by strong mutual interdependencies among species, processes, and environmental conditions (Groot et al., 2010). Understanding how key ecological functions determine the supply of ecosystem services, and how these functions depend on biodiversity, is crucial for identifying sustainable, nature-based solutions (Cohen-Shacham et al., 2016). Equally important is recognizing how substituting natural processes with technological alternatives may disrupt ecological integrity and reduce long-term system resilience.

Although humans have always depended on nature, modern societies often overlook this dependency. The failure to recognize the intrinsic and utilitarian value of biodiversity and its fundamental contribution to human well-being has been cited as one of the main reasons for environmentally damaging behaviours. A deeper understanding of the trade-offs and synergies among ecosystem services can help realign human actions with ecological sustainability (Bennett et al., 2015). In the context of "Little Texas Wonocolo", the system can be conceptualized as a coupled socio-ecological system, in which traditional oil mining acts as the primary social and economic driver, while the surrounding ecosystem components including soil, water, vegetation, and microclimate form the ecological domain. Oil extraction, particularly when conducted through traditional techniques, often produces waste and accidental spills that can contaminate soil and groundwater. These impacts alter both the regulating services (such as water purification, soil fertility, and microclimate regulation) and the provisioning services (such as clean water supply and agricultural productivity) of the ecosystem.

Within this socio-ecological system, a clear trade-off arises between: The provisioning service of crude oil extraction, which supports local livelihoods and contributes to household and regional income; and The provisioning and regulating services of freshwater, which provide essential ecosystem functions such as drinking water, irrigation, and habitat support (Schirpke et al., 2019). Understanding and managing these trade-offs is key to balancing short-term economic gains with long-term ecological sustainability. Strengthening biodiversity-based ecosystem functions can enhance both the productivity and resilience of the system, ensuring that socio-economic development does not come at the expense of environmental degradation.

Socio-Ecological Characteristics and Interaction

Although people have always depended on nature, in modern societies it is easy to lose sight of the fact that we still do. Indeed, many have argued that our failure to recognize the value of nature and especially the contribution that biodiversity makes to our well-being, explains much of our damaging behaviour towards the environment (Pascual et al., 2017).

All relationships in social-ecological-systems are driven by different aspects of biodiversity (Cardinale et al., 2012; Naeem et al., 2016). These interactions should be analysed in order to set up biodiversity strategies. The creation of ES is founded on very complex schemes of ecological interactions with very high mutual interdependencies. Understanding how key functions determine ES supply and how they depend on biodiversity and understanding the effect of short-cutting these functions by technological variants, is crucial in the search for nature-based solutions (Balvanera et al., 2014; Díaz et al., 2019; Howe et al., 2014).

Water quality measurements were conducted at 40 sampling points located within the settlement areas surrounding the traditional oil mining zone. Spatial distribution can be seen in Figure 2.

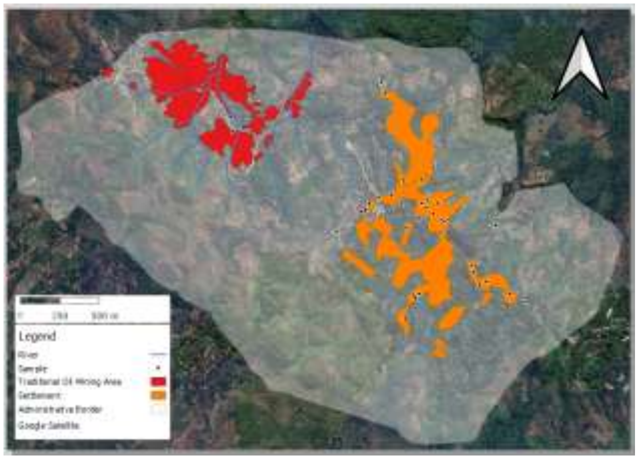

Figure 2. Spatial feature of traditional oil mining area, settlement and sample

The selection of these sampling points aimed to represent variations in household access to groundwater sources potentially affected by mining activities. At each point, four key physicochemical parameters were measured to assess groundwater quality: pH, electrical conductivity, temperature, and salinity (WHO, 2017; Dhea et al., 2023). These parameters were chosen because they serve as fundamental indicators of water suitability for domestic use and reflect potential contamination or mineral enrichment processes caused by subsurface hydrocarbon extraction (Chapra, 2008; Hilson et al., 2017; Macháček, 2019). Measurements were taken directly in the field using portable water-quality instruments that had been calibrated prior to use to ensure accuracy and consistency of results can be seen in Table 3.

Table 3. Result of Measurement Groundwater Quality

Descriptive Statistics	pH	Conductivity (ms/cm)	Temperature (^{o}C)	Salinity (PSU)
Min	6.45	0.44	22.77	0.0
Max	7.90	2.23	30.85	0.0
Mean	7.41	0.85	27.51	0.0

Descriptive statistical analysis of water quality parameters measured at 40 sample points in the organization's area is presented in Figure 3. The pH values ranged from 6.45 to 7.90, with an average of 7.41, indicating that most soil air samples were neutral to slightly alkaline. This range is within the WHO drinking water quality standards and the Indonesian Ministry of Health Regulation (6.5–8.5), so the air quality is generally considered safe from acidity levels.

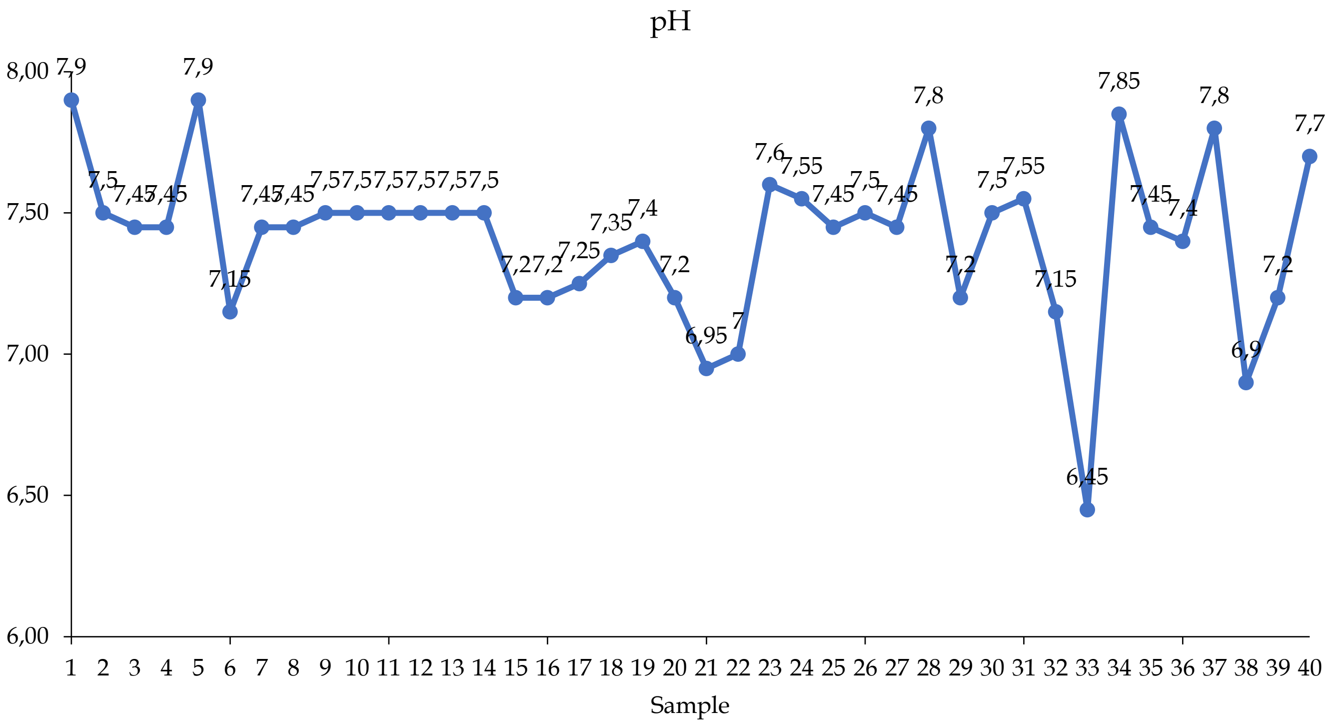

Figure 3. Result measurement of water pH

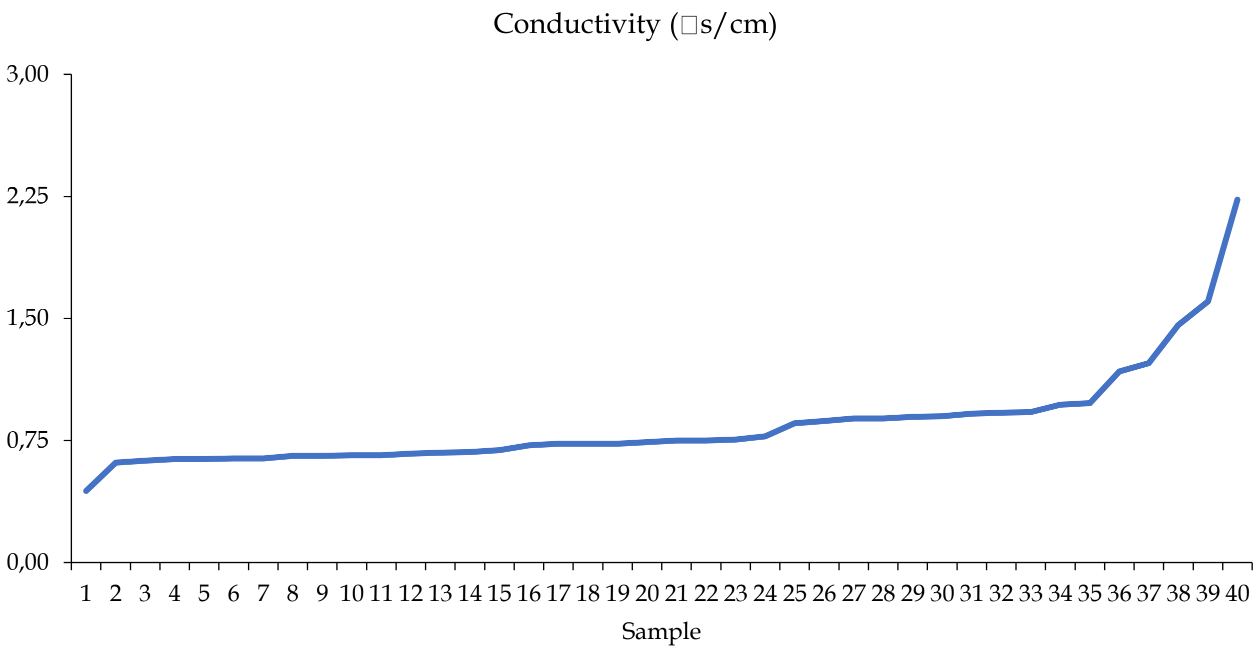

Figure 4. Result Measurement of Conductivity

Table 4. Classification of pH

Classification	Count of pH Class
6.5 - 7.0	3
7.0 - 7.5	19
7.5 - 8.0	18
Grand Total	40

Electrical conductivity measurement in Figure 4 has value ranged from 0.44 to 2.23 mS/cm, with an average of 0.85 mS/cm, reflecting variations in dissolved ion levels between sampling locations. Higher conductivity values may indicate higher mineral content, particularly at points adjacent to traditional oil mining areas (Andrio et al., 2024).

Table 5. Classification of conductivity

Range	Count of Conductivity
< 0.75	20
0.75–1.5	18
> 1.5	2
Grand Total	40

Water temperature in Figure 5 ranged from 22.77 to 30.85°C, with an average of 27.51°C, which is within the normal range for groundwater in tropical climates. The relatively narrow temperature variation indicates stable subsurface thermal conditions without significant external heat influence.

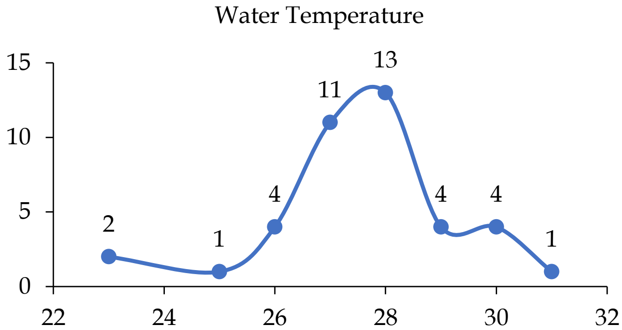

Figure 5. Result Measurement of Water Temperature

Salinity measurements across all sampling points were recorded at values 0.0 PSU. According to drinking water quality references from the World Health Organization, freshwater is generally characterized by very low salinity, and values below 0.5 PSU are classified as non-saline and suitable for domestic use. Therefore, the measured salinity levels in the study area indicate that the groundwater is not affected by saltwater intrusion or significant chloride contamination. The results suggest that, despite the proximity to traditional oil mining activities in the Wonocolo area, there is no evidence of salinity-related pollution. Overall, the descriptive statistics indicate that the physical and chemical quality of groundwater in the storage area surrounding the Wonocolo traditional oil mining site remains within safe limits. Although variations in conductivity values require further investigation to identify possible localized increases in dissolved minerals.

Socio-Ecological Dynamics in Traditional Oil Mining

Field evidence from Wonocolo illustrates that traditional oil mining is more than an economic practice. It is embedded in the community's social fabric and cultural identity. Local narratives reveal that many households depend on oil mining activity, while others benefit from derivative activities such as guiding visitors, managing small museums, operating food stalls, or providing accommodation for students and researchers. This socio-economic diversification shows that Wonocolo functions as a Social-Ecological in which human agency and ecological processes interact and co-evolve.

Ecologically, the area is characterized by gently undulating karst hills, teak plantations, and small plots of rain-fed maize. A shallow aquifer underpins freshwater supply, but its resilience is shaped by seasonal rainfall and land-use pressures. During prolonged dry spells, residents often experience groundwater scarcity and adapt by digging additional wells, buying bottled water, or walking to nearby artesian springs (Aris & Arifin, 2023). However, mining practices particularly the discharge of drilling waste into local waterways pose risks to the hydrological system by altering natural filtration processes. These observations confirm feedback loops typical of SES: economic incentives drive oil exploitation, which can degrade ecosystem functions, subsequently affecting household welfare and prompting adaptive behavior.

Trade-Offs between Ecosystem Services: Oil Revenue versus Groundwater Quality

The relationship between oil production and groundwater quality in Wonocolo reflects a clear ecosystem services trade-off. Crude oil represents a provisioning service that sustains household income and supports village-level economic stability (Rahman et al., 2019; Rahayu & Ahyadi, 2024). Yet, the same landscape supplies another critical service: the provision and regulation of clean water for domestic, agricultural, and ecological uses. As shown by field measurements, groundwater pH remained within acceptable limits (6.4–8.0), and organoleptic characteristics were mostly normal. Nevertheless, conductivity readings at certain locations such as House 27 (2.26 mS/cm) and House 29 (1.61 mS/cm) indicate higher concentrations of dissolved ions, which may derive from mineral leaching or contamination associated with oil activities (Hilson et al., 2017; Macháček, 2019).

Qualitative data enrich these findings. Residents' preferences regarding drinking water reveal differing perceptions of risk: some rely on bottled or refilled water due to the "hardness" of well water, while others boil and filter groundwater for consumption. These practices mirror a balancing act between cost, convenience, and safety. The trade-off becomes sharper when increased oil output threatens to exceed the ecosystem's capacity to filter pollutants, undermining water quality and potentially increasing treatment costs or health risks (Bennett et al., 2015). As highlighted by the TEEB (2010), maximizing one service oil revenue can compromise another clean water especially where thresholds related to soil permeability, vegetation cover, and pollutant loads are surpassed (Mangallo & Oktaviani, 2023).

Beneficiaries and Equity Dimensions

Another layer of complexity lies in the distribution of benefits and risks across social groups. Wealthier households, often those owning oil wells or involved in tourism, can more easily purchase bottled water or invest in alternative supplies. In contrast, economically vulnerable groups, including widows and elderly residents, rely heavily on communal wells and are more exposed to fluctuations in groundwater quantity and quality (Pascual et al., 2017). This uneven access underscores the importance of addressing equity when managing ecosystem services (Zhang et al., 2023). Without governance mechanisms that integrate environmental safeguards with social justice, trade-offs may deepen socio-economic disparities.

The findings demonstrate that the issue in Wonocolo is not merely technical balancing "oil versus water" but relational, rooted in how people manage extraction, waste, and conservation within a coupled human–environment system. Sustainable governance therefore requires an integrated framework that aligns economic objectives with ecological resilience (Liu et al., 2023; Ostrom, 2009; Schlüter et al., 2012). Possible strategies include: establishing local rules for safe waste handling and spill prevention; planting vegetative buffer zones to intercept contaminants before they reach wells; implementing systematic groundwater monitoring; and promoting heritage-based tourism and environmental education to diversify income sources.

Such measures resonate with the principles of nature-based solutions, offering a pathway to reduce environmental pressures while sustaining livelihoods. They also reinforce the value of participatory approaches, where communities, local authorities, and researchers collaborate to set priorities, identify thresholds, and design adaptive responses.

By framing traditional oil mining as part of a socio-ecological system and evaluating its ecosystem service trade-offs, this study contributes to wider debates on resource governance in small-scale extractive landscapes. It underscores the need to integrate biophysical assessments (e.g., groundwater monitoring) with qualitative insights into social behavior, risk perception, and institutional capacity. Such integration enriches our understanding of how to balance short-term economic benefits with the long-term sustainability of vital services such as clean water. The Wonocolo case may inform policies in other artisanal mining regions where similar tensions between livelihoods and ecosystem health persist.

Conclusion

The study in "Little Texas Wonocolo" reveals that traditional oil mining is not merely a technical issue of extraction, but a complex socio-ecological challenge where economic benefits from oil production directly compromise the sustainability of water resources. Laboratory results show elevated electrical conductivity in several residential wells (notably Houses 27 and 29), indicating increased concentrations of dissolved ions. These findings provide evidence of localized seepage of oil-related waste and saline produced water into the shallow aquifer system. Thus, the issue should no longer be framed as a potential environmental risk, but as an ongoing process of environmental degradation that threatens the achievement of United Nations Sustainable Development Goal 6 (Clean Water and Sanitation. The trade-off in Wonocolo is a stark choice between immediate provisioning services (oil revenue) and the long-term regulating services of the ecosystem. By prioritizing crude oil production, the ecosystem's natural ability to provide clean water and maintain soil health is severely eroded. This loss of ecosystem multifunctionality creates an economic burden, as the short-term financial gains from mining are offset by the rising costs of procuring clean water and addressing health risks. From a socio-ecological perspective, this degradation is not felt equally; lower-income groups are the most vulnerable, as they lack the financial means to shift to alternative water sources, such as bottled water, unlike wealthier households. This dynamic exacerbates social inequities, hindering the progress of SDG 10 (Reduced Inequalities).

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Author Contributions

Ifan Deffinika led the conceptualization and initial manuscript writing. Field data were collected by Adelisa Rizki Zaharani and Novi Silvia. Data analysis was conducted by Alfi Sahrina and Dicky Arinta, while spatial analysis and interpretation were carried out by Inanditya Widyana Putri. All authors contributed to manuscript revision and visualization.

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Conflicts of Interest
The authors declare that there is no conflict of interest. There are no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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