

## Strategy for Management and Monitoring of Groundwater Quality in Oilcontaminated Soil Recovery Areas in Siak Regency, Riau Province

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### Abstract

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#### Keywords:

Groundwater Quality; PKM  
15.800 Lukut; Oil-Contaminated  
Soil; Total Petroleum  
Hydrocarbon (TPH).

Groundwater is an essential natural resource that supports ecological balance and human life; however, it is highly vulnerable to contamination from industrial activities, particularly oil and gas operations. Oil spills can cause significant environmental degradation, affecting soil quality, groundwater systems, and the socio-economic conditions of surrounding communities. This study aims to analyze the impact of oil contamination and to formulate strategies for managing and monitoring groundwater quality in the oil-contaminated soil recovery area at PKM 15,800 Lukut, Siak Regency, Riau Province. The research was conducted from May to December 2025 using a mixed-methods approach that combines environmental monitoring, laboratory analysis of groundwater samples, field observations, and socio-economic surveys of local communities. Groundwater samples were analyzed for Total Petroleum Hydrocarbon (TPH) parameters, including short-chain (C6–C9) and long-chain (C10–C36) hydrocarbons. The results show that although traces of TPH were detected during early monitoring, subsequent monitoring indicates that groundwater quality has remained below the established environmental quality standards. Ecologically, the affected area shows signs of ecosystem recovery through the presence of pioneer vegetation and diverse fauna, while socio-economic impacts include reduced oil palm productivity and community concerns regarding environmental safety. The study concludes that groundwater quality in the study area is generally stable after remediation, and that an integrated and proactive strategy—incorporating community participation, institutional support, and continuous environmental monitoring—is essential for sustainable groundwater management and long-term environmental recovery.

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## INTRODUCTION

Groundwater is water resulting from the infiltration of surface water into the soil, which subsequently forms an aquifer system. The movement of groundwater occurs through pores or spaces between soil grains that are saturated with water, thereby enabling the flow and storage of water in subsurface layers (Saputra, 2016; Fetter, 2018). As one of the most crucial geological resources, water plays a fundamental role in sustaining life. Within the hydrological cycle, water functions as a universal solvent due to its ability to dissolve and transport various elements and chemical compounds from the geological media through which it passes (Noor, 2011; Freeze & Cherry, 2019).

Groundwater is conceptually defined as water present within soil layers, both in the unsaturated and saturated zones, and is highly susceptible to contamination due to anthropogenic activities, including those from the oil and gas industry (Darwis, 2018; Todd &

Mays, 2020). Geographically, the location of Oil Contaminated Soil (TTM) recovery in Siak Regency, Riau Province, is situated approximately  $\pm 115$  km from the operational area of PT Bumi Siak Pusako. PT Bumi Siak Pusako has managed the Coastal Plain and Pekanbaru (CPP) Block since 2002, after previously being operated by Caltex Pacific Indonesia since 1971. In oil and gas operational activities, oil spills have the potential to cause serious impacts on soil and groundwater quality if not managed systematically and sustainably (ITOPF, 2018; IPIECA, 2020). Therefore, the restoration of land contaminated with hazardous and toxic waste (B3) must be conducted in accordance with the Regulation of the Minister of Environment Number 33 of 2009, which includes the stages of planning, implementation, evaluation, and monitoring. The Environmental Function Recovery Plan (RPFLH) document has been approved through Letter Number S.1577/MENLHK-PSLB3/PKTDLB3/PLB.4/8/2020.

The dig-and-fill method applied in oil-contaminated soil remediation activities is a physical remediation approach commonly used in areas with high contamination levels. This method requires strict field supervision to ensure that B3 waste residues are handled in accordance with environmental quality standards (EPA, 2019; KLHK, 2021). Following the implementation of recovery, the installation of monitoring wells in upstream and downstream areas, along with post-recovery monitoring for one year, is mandated by the Regulation of the Minister of Environment Number 33 of 2009.

The obligation to monitor groundwater quality is further emphasized in the Decree of the Minister of Environment and Forestry of the Republic of Indonesia Number SK.5402/MENLHK-PSLB3/PKTDLB3/PLB.4/8/2021 concerning the determination of the completion status of B3-contaminated land restoration at the PKM 15,800 Lumut location, Siak Regency, Riau Province. In point G, it is stated that the Joint Operation Agency of PT Bumi Siak Pusako–Pertamina Hulu is required to monitor groundwater quality through designated monitoring wells. The total volume of petroleum-contaminated soil that has been treated reached  $133.18 \text{ m}^3$ , equivalent to 204.92 tons, all of which have been documented through logbooks, Certificates of Treatment (CoT), and internal documentation of B3 waste management (MoEF, 2021; BBKSDA Riau, 2022).

The installation of monitoring wells using the dry drilling method is a recommended technical approach in environmental monitoring, as it minimizes the risk of cross-contamination during the drilling process (ASTM, 2018; Nielsen & Nielsen, 2020). Therefore, this research is important for assessing environmental conditions and subsurface characteristics, as well as providing a basis for continuous monitoring of groundwater quantity and quality (Groundwater Monitoring/GWM).

Several previous studies have demonstrated that various methods have been developed to address environmental pollution, particularly in soil and water. Charlena et al. (2013) showed that the landfarming bioremediation technique, with the addition of compost and bacteria, can reduce Total Petroleum Hydrocarbon (TPH) content in oil-contaminated soil by up to 48% within 16 weeks. Meanwhile, Zulkifliani (2017) developed an integrated remediation technique combining physical, chemical, and biological methods to separate oil from contaminated soil, which proved effective in reducing oil content below permissible

thresholds. Priadie (2012) also emphasized that bioremediation using microorganisms, such as bacteria, can serve as an alternative solution for controlling water pollution, as it is capable of degrading various pollutants, including heavy metals and organic compounds. Furthermore, Suryadi, Garnadi, and Notodarmojo (2017) applied the Analytical Hierarchy Process (AHP) method to formulate strategies for controlling groundwater vulnerability, identifying the limitation of groundwater extraction as the most effective strategy for maintaining water quality and sustainability.

This research is a follow-up study of oil-contaminated soil monitoring activities that have previously been completed. Accordingly, this study represents periodic monitoring conducted on a semester basis, aiming to ensure that post-recovery groundwater quality continues to meet environmental quality standards and does not pose further risks to the surrounding ecosystem (EPA, 2020; KLHK, 2023; Wibowo et al., 2024). Based on these considerations, this study is entitled "Strategies for Management and Monitoring of Groundwater Quality in the Oil Contaminated Soil (TTM) Recovery Area at the PKM 15,800 Lumut Location, Siak Regency, Riau Province."

Based on the background description, the following problems can be identified:

1. What is the impact of the *oil spill* on the ecological, economic and social aspects of the community at the location of PKM 15,800 Lukut?
2. What is the current condition of groundwater quality at the PKM 15,800 Lukut location which was polluted by oil spills after the removal of contaminated soil?
3. What is the strategy for monitoring and managing groundwater quality and recovery efforts carried out in dealing with *oil spills* at the location of PKM 15,800 Lukut affected by oil spills?

This study aims to analyze the Management and Monitoring Strategy of Groundwater Quality in the Oil Contaminated Soil (TTM) Recovery Area at the PKM 15,800 Lumut Location, Siak Regency, Riau Province. This research specifically aims to:

1. Analyzing the impact of *oil spill* on the ecological, economic and social aspects of the community at the location of PKM 15,800 Lukut.
2. Analyzing the current condition of groundwater quality at the PKM 15,800 Lukut location which was polluted by oil spills after the removal of contaminated soil.
3. Formulating strategies for monitoring and managing groundwater quality and recovery efforts carried out in handling *oil spills* at the PKM 15,800 Lukut location.

The benefits of this research are:

1. Providing information about Oil Contaminated Soil (TTM) handling activities at the location of oil spills (Oil Spill).
2. For the community, they can add knowledge and insight about oil contaminated land management based on applicable laws and regulations.
3. Providing information to readers so that it is expected to be used as a reference for the development of knowledge related to the problem being researched.

## **METHOD**

**Place and Time of Research**

This research was carried out in the period from May to December 2025 and is located at PKM 15,800 Lukut, Siak Regency, Riau Province, with coordinates of 0°43'41.64" N and 101°30'30.59" E.

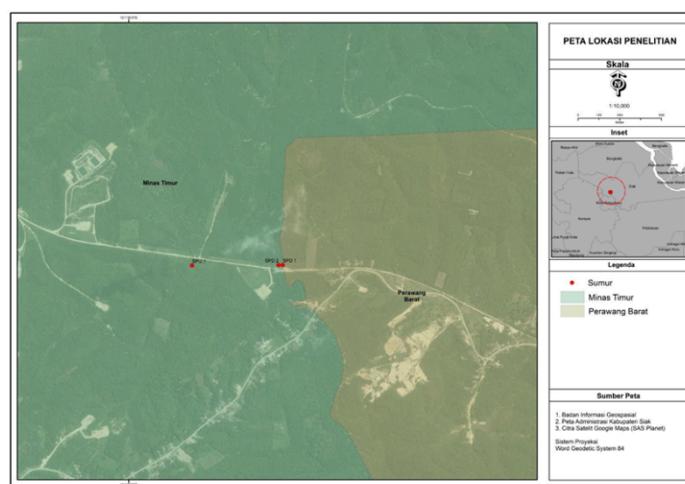
**Description of the Research Location**

The location of the PKM 15,800 Lukut leak, administratively located in West Perawang Village, Tualang District and borders the East Minas Village area, Minas District. The north and east are bordered by oil palm plantations owned by the community, the south is bordered by oil roads/pipelines and the west of the study site is bordered by the Lukut River. The topography at the study location has a slope of 5% to 10% which is categorized as sloping (Van Zuidam, 1985) with a slope pattern from east to west.

The location of the well is monitored based on the Decree of the Minister of Environment and Forestry of the Republic of Indonesia SK.5402/MENLHK-PSLB3/PKTDLB3/PLB.4/8/2021 concerning the Determination of the Status of the Completion of the Restoration of B3 Waste-Contaminated Land at the PKM 15,800 Lumut Location, Siak Regency, Riau Province by the Joint Operations Agency of PT. Bumi Siak Pusako – Pertamina Hulu is as follows:

**Table 1.** Research Location Observation Points

Upstream Monitoring Well 1	U. 0° 43' 41.50"	T. 101° 30' 30.29"
Downstream Monitoring Well 1	U. 0° 43' 42.60"	T. 101° 30' 29.90"
Downstream Monitoring Well 2	U. 0° 43' 42.60"	E. 101° 30' 29.09"



**Figure 1.** Location of data collection points (Source: Google Earth, 2026)

**Materials and Tools**

The tools and materials used in this study include: Tools for drilling and installing monitoring wells, namely drilling is carried out by direct rotary method using the Spindle machine type. Soil samples were taken using a spiral auger with a length of 0.5 m and 1 m

using (Drilling machine type TOHO D-01 and YBM-01, Yanmar 15.5 PK drive unit, Sanchin 4 water pump unit, Yanmar 5.5 PK drive unit, Firman water pump unit, PVC pipe, Gravel Pack, Bentonite seal, drill handlebar (rod), Tripod, Dipmeter, drill bit).

Groundwater quality monitoring sampling was carried out based on the observation points of the research location in Table 3.1. Groundwater quality testing was carried out in the laboratory to determine the results of groundwater analysis for the parameters of Total *Petroleum Hydrocarbon* (TPH) Short Chain (C6-C9) and Total *Petroleum Hydrocarbon* (TPH) Long Chain (C10-C36). Based on the Decree of the Minister of Environment and Forestry of the Republic of Indonesia SK.5402/MENLHK-PSLB3/PKTDLB3/PLB.4/8/2021. The tools used for the interview are cameras and office stationery, while the materials are observation interview sheets (Appendix 1 and Appendix 2).

### **Types of Data Sources**

The types of data used in this study are qualitative and quantitative data that describe the strategy for managing and monitoring groundwater quality and to describe the quality of groundwater samples, based on the knowledge of workers and the community in managing groundwater quality polluted by oil spills. The data sources used in this study include:

1. Data Primer
2. Data Seconds

### **Population and Sample**

The population in this study is defined as a whole of research objects or subjects that have certain characteristics and qualities that are determined by the researcher to be studied systematically, so that generalizing conclusions can be drawn (Sugiyono, 2001; Arikunto, 2016). Samples are part of the population that is chosen to represent the characteristics of the population, both in terms of number and characteristics (Sugiyono, 2019).

Based on this understanding, the population in this study is the community in PKM 15,800 Lukut while the sample in this study is determined to include workers from PT Bumi Siak Pusako who are involved in groundwater sampling activities and people who live around the research site, especially in the area adjacent to the PKM 15,800 Lukut location, Siak Regency, Riau Province.

Data collection from respondents was carried out through the dissemination of questionnaires and structured interviews to obtain relevant information according to the research variables. In addition, groundwater sampling was carried out at three observation points at the PKM 15,800 Lukut Location, Siak Regency, Riau Province, by the Joint Operations Agency of PT Bumi Siak Pusako-Pertamina Hulu. The samples taken were adjusted to the research variables that had been determined, so that they were able to represent the environmental conditions at the study location (Creswell, 2014; Sugiyono, 2019).

## **RESULTS AND DISCUSSIONS**

### **4.2 Impact of Oil Spill (*oil spill*) on the Ecology, Economic and Social Aspects of the Community at the Location of PKM 15,800 Lukut**

**Table 2.** Types of Plants Found in PKM 15,800 Lukut

No.	Name Indonesia	Latin Names
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1	São Paulo	<i>Elaeis guineensis</i>
2	Guava	<i>Psidium guajava</i>
3	Back to the Wind	<i>Mallotus paniculatus</i>
4	Simpur	<i>Dillenia indica</i>
5	São Paulo	<i>Macaranga gigantea</i>
6	Mahang	<i>Macaranga triloba</i>
7	Akasia	<i>Acacia mangium</i>
8	Bintangor	<i>Calophyllum</i> sp.
9	Slot	<i>Gonystylus</i> sp.
10	Surian	Until I Died

Source: Personal observation data

The results of ecological monitoring at the PKM 15,800 Lukut location show that the area affected by the petroleum spill is still overgrown by a number of vegetation types with different levels of tolerance to degraded environmental conditions. The existence of this vegetation reflects the adaptability of terrestrial ecosystems to petroleum pollution disturbances, as well as being an early indicator of the post-spill ecological recovery process (Leewis *et al.*, 2024; Peijnenburg *et al.*, 2023).

Based on the results of the vegetation inventory in Table 4.1, ten types of plants were identified scattered in the contaminated area, consisting of cultivated plant types, pioneer species, and secondary forest trees (Lestari *et al.*, 2021; Rahayu & Nugroho, 2022). Species found include palm (*Elaeis guineensis*), guava (*Psidium guajava*), backwind (*Mallotus paniculatus*), crimson (*Dillenia indica*), mahang (*Macaranga gigantea* and *Macaranga triloba*), acacia (*Acacia mangium*), bintangor (*Calophyllum* sp.), ramin (*Gonystylus* sp.), and surian (*Toona south*) (Table 1).

The dominance of pioneer species such as *Macaranga* spp., *Mallotus paniculatus*, and *Acacia mangium* indicates that the affected areas have experienced significant ecological disturbances. These species are known to have a fast growth rate, high tolerance to nutrient-poor soil conditions, and adaptability to contaminated environments, so they often appear on disturbed land or after environmental disturbances (Suryadi *et al.*, 2020; Fitriani *et al.*, 2023). The presence of this pioneering vegetation indicates an early succession process as a natural response to the pressures of petroleum pollution.

The existence of oil palm (*Elaeis guineensis*) and guava (*Psidium guajava*) shows that some of the affected areas were previously land used by the community. This indicates that petroleum spills not only have an impact on natural ecosystems, but also have the potential to affect the function of productive land and socioeconomic activities of the surrounding communities (Prasetyo *et al.*, 2022).

In addition, the discovery of forest tree types such as bintangor (*Calophyllum* sp.), ramin (*Gonystylus* sp.), and surian (*Toona sureni*) shows that despite pollution disturbances, there are still vegetation elements with high ecological value. The existence of these types indicates that not all forest vegetation structures have been completely destroyed, and there is still the potential for a gradual restoration of ecological functions if supported by sustainable environmental management and monitoring (Leewis *et al.*, 2024; Barbour *et al.*, 2020).

Ecologically, the vegetation structure that remains in the petroleum-contaminated area at PKM 15,800 Lukut plays an important role in supporting the environmental restoration process. Vegetation serves as a ground cover, erosion controller, and microhabitat provider for other organisms. In addition, some plant types are known to have natural phytoremediation capabilities, such as increasing soil microbial activity and accelerating the degradation of petroleum hydrocarbons (Hidayat *et al.*, 2021; Leewis *et al.*, 2024).

Thus, the composition of vegetation found in the area affected by the petroleum spill in PKM 15,800 Lukut shows that the ecosystem is in the early to medium recovery phase. The existence of pioneer species, cultivated crops, and forest trees is an important indicator in assessing the level of ecological disturbance as well as the potential for successful restoration of environmental functions after oil spills (Peijnenburg *et al.*, 2023; Fitriani *et al.*, 2023).

The results of fauna observations in the PKM 15,800 Lukut area show a diversity of animal species, even though the area is affected by petroleum spills. The fauna found consists of birds, mammals, reptiles, and insects in Table 2, which shows that despite ecological disturbances, ecosystems are still able to support the life of various types of animals (Table 3).

**Table 3.** Types of Birds Found in PKM 15,800 Lukut

No.	Name Indonesia	Latin Names
1	Merbah cerukcuk	<i>Pycnonotus goiavier</i>
2	Eurasian Birds	<i>Passer montanus</i>
3	Shrub	<i>Halcyon smyrnensis</i>
4	Bondol rawa	<i>Lonchura malacca</i>
5	Rock kites	<i>Hirundo tahitica</i>
6	Bondol beijing	<i>Lonchura punctulata</i>
7	Cockroach Finches	<i>Pycnonotus aurigaster</i>
8	River Short	<i>Todiramphus chloris</i>
9	Bondol Eagle	<i>Haliastur indus</i>
10	Eagle Brontok	<i>Nisaetus cirrhatus</i>
11	Kuntul Kerbau	<i>Bubulcus ibis</i>

Source: Personal observation data

Based on Table 3, there are eleven species of birds identified at the location of PKM 15,800 Lukut. Some common species such as the Niche Squirrel (*Pycnonotus goiavier*), Finches (*Pycnonotus aurigaster*), and Eurasian Birds (*Passer montanus*) show adaptability to habitat changes, including areas that are subject to oil contamination.

In addition, predatory species such as the Bondol Eagle (*Haliastur indus*) and the Brontok Eagle (*Nisaetus cirrhatus*) were also found, which play an important role in maintaining the balance of the ecosystem by controlling the population of small birds and small mammals. The presence of water birds such as the Buffalo Egrets (*Bubulcus ibis*) also shows that there is a water source that can still be used for animal life despite contamination. The dominance of insect-eating and seed-eating birds indicates the existence of a post-spill ecosystem adjustment process, in which species that are more tolerant of disturbances can still

survive. This phenomenon is in line with the theory of ecological succession, in which opportunistic species emerge early on disturbed ecosystems.

**Table 4.** Other Types of Animals Found Around PKM 15,800 Lukut

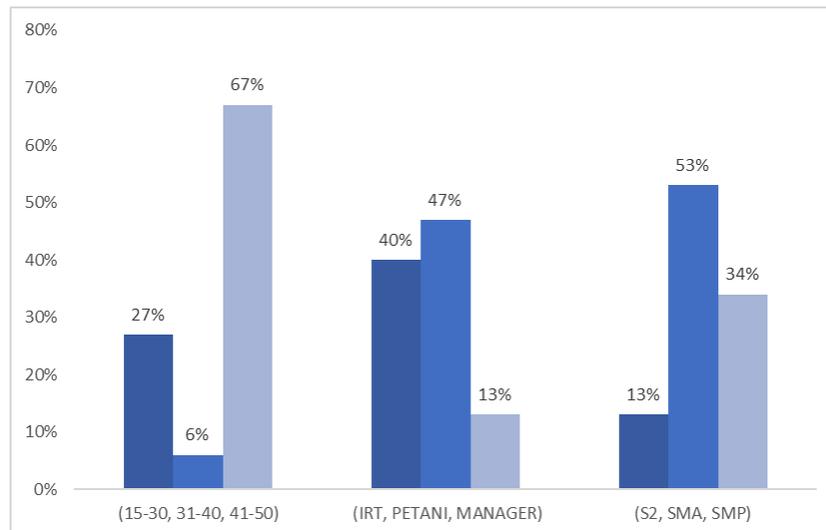
No.	Name Indonesia	Latin Names
1	Long-tailed monkey	<i>Macaca fascicularis</i>
2	Wild Boar	<i>Your scrofa</i>
3	Kongkang gading	<i>Hylarana erythraea</i>
4	Kongkang baram	<i>Pulchrana baramica</i>
5	Lizard	<i>Varanus salvator</i>
6	Gadung snake	<i>Ahaetulla prasina</i>
7	Layang-layang api	<i>Hirundo rustica</i>
8	Three-eyed butterfly	<i>Ypthima pandocus</i>
9	Kupu-kupu kuning	<i>Eurema sari</i>
10	Rhinoceros dragonfly	<i>Orthetrum sabina</i>
11	Curved mesh dragonfly	<i>Neurothemis ramburii</i>

Source: Personal observation data

The diversity of fauna found at the PKM 15,800 Lukut location shows the initial recovery process of the ecosystem after the petroleum spill. Although some species show tolerance to disturbances, there are still species that have specific habitat needs, such as semi-aquatic reptiles and birds of prey, which can be indicators of habitat quality (Barbour *et al.*, 2020). Therefore, advanced monitoring is needed to ensure the sustainability of the recovery process, including the protection of pioneer vegetation and forest trees that are the source of feed and animal habitat and maintaining ecological interactions between biotic components in ecosystems (Leewis *et al.*, 2024; Fitriani *et al.*, 2023).

#### 4.2.2 Social Condition of the PKM Community 15,800 Lukut

The oil spill that occurred in the PKM 15,800 Lukut area had a significant impact on the social conditions of the community, especially in the three RTs closest to the scene of the incident. Based on field data, the composition of respondents showed that the affected community consisted of 15 people who were selected through *purposive sampling* techniques, namely men (47%) and women (53%). Most of them are in the productive age group (15–30 years and 41–50 years), which according to Tjiptoherijanto (2011) is the group with the highest level of economic and social activity in the community. This condition shows that oil spills not only disrupt the ecological environment, but also disrupt the social dynamics of people who are in an age phase with great economic needs and family responsibilities.



**Figure 2.** Age, Occupation and Education Data of the Lukut PKM Community 15,800

Based on Education in Figure 4.2, the majority of the 15,800 PKM people have high school/vocational education (53%) with the secondary level (SMP) at 34%. This relatively diverse education affects the level of public understanding of environmental risks. Based on the study of Mustapha *et al.* (2020), people with secondary-high education tend to be more responsive to the issue of oil pollution and more quickly adapt in finding social and economic mitigation strategies. However, community groups with junior high school education, most of whom work as farmers, are more vulnerable to being affected, both socially and economically, because they are directly dependent on the surrounding land and natural resources. This is in line with the findings of Nurlaili & Puspita (2021) that farmers in oil palm plantation areas in Riau are more vulnerable to environmental disturbances due to their dependence on one main source of income.

Socially, oil spills also affect people's psychological safety. Based on the results of the interviews, the community was a little worried about water quality, children's health, and the continuity of daily activities such as gardening and raising livestock. These findings are in line with the report of Al-Ghussain & Jenner (2020), which states that oil pollution in rural settlements causes increased social anxiety and decreased sense of security due to uncertainty regarding long-term impacts. This concern is higher in the women's group (IRT) which plays a major role in maintaining family health, as also found in a study by Sari & Handayani (2021) on the social impact of environmental pollution on households in rural areas.

Oil spills also have an impact on people's social interactions. Some respondents said that routine activities such as mutual cooperation, RT meetings, and gathering activities were reduced because people were more careful approaching the affected areas. This is in line with the research of Dzigbede *et al.* (2018) which explains that environmental pollution often reduces social participation because people avoid areas that are considered unsafe. In addition, oil spills can affect social cohesion due to differences in perceptions between directly and indirectly affected communities, especially related to compensation and assistance (Umar *et al.*, 2024).

In the context of the people of Minas District, who have a large economic dependence on the agricultural and oil palm plantation sectors, the oil spill exacerbates existing social vulnerabilities. Dependence on one main commodity makes people not have many alternatives when sources of income are disrupted (Fitriani *et al.*, 2023). Therefore, oil spills are not only an environmental problem, but also have social impacts that include a decline in quality of life, an increase in psychological burden, a decrease in income, and the potential for social conflicts at the community level.

#### **4.2.3 Economic Conditions PKM Community 15,800 Lukut**

The results of the analysis of the socio-economic characteristics of the respondents show that most respondents occupy privately owned houses (60%), while the rest live in rented houses (40%). The condition of the respondents' residential buildings is generally classified as permanent (54%), with the dominant residential area ranging from 50–100 m<sup>2</sup>. In terms of the physical quality of buildings, the majority of houses have ceramic flooring (87%) and two or more bedrooms, reflecting a relatively adequate level of occupancy comfort.

From a sanitation perspective, most respondents already have adequate basic sanitation facilities. The primary source of water for bathing, washing, and toileting (MCK) generally comes from wells, both borewells and dug wells, and all houses are equipped with latrine/toilet facilities (100%). Meanwhile, the source of clean water is reported to originate entirely from North Sumatra (100%). For daily water needs, including drinking water, respondents generally rely on borewell water (100%). This condition indicates that access to clean water remains highly dependent on groundwater sources. In terms of energy use, all respondent households are supplied with electricity from PLN (100%) and use LPG gas as the main source of household energy (100%), indicating very good access to basic energy services in the study area.

Based on income levels, respondents have an average monthly income equal to or above the Riau Provincial Minimum Wage (UMP) in 2023, with a range between IDR 4,000,000 and IDR 7,500,000 per month. The UMP of Riau Province in 2025 is set at IDR 3,508,776, based on the Decree of the Governor of Riau concerning the Provincial Minimum Wage for 2025. This relatively high income level contributes to the ability of respondents to meet their living needs and acquire various assets to support daily activities.

In terms of mobility, almost all respondents have private means of transportation, with motorcycles being the most common (38%). In addition, all respondents (100%) own mobile phones as a means of communication, reflecting a high level of accessibility to communication technology in the study area.

The community around PKM 15,800 Lukut experienced economic impacts due to the oil spill, although these did not result in severe overall losses. Daily economic activities, such as trading and working in the service sector, continued as usual. However, oil palm plantations, which are a primary source of income for the community, were directly affected. This is evidenced by a decline in oil palm yields in several areas impacted by the oil spill. According to Yuliasari (2019), oil spills can inhibit plant physiological processes and reduce land productivity. Similarly, Ramadhan and Putra (2021) found that oil contamination in soil can reduce crop yields and lower production quality. These findings are consistent with field

conditions, where several oil palm plantations experienced decreased productivity following the spill.

Under normal conditions, oil palm trees aged 7–8 years are harvested twice a month, producing an average of 1.75–3 tons of fresh fruit bunches (FFB), generating an income of IDR 4,000,000–IDR 7,500,000 per month. However, after the oil spill affecting approximately 3.5 hectares, the productivity of oil palm trees aged 9–10 years declined significantly, despite regular fertilization. Production, which previously reached several tons, decreased by 600–800 kg per month, resulting in an income loss of approximately IDR 1,500,000–IDR 2,000,000 (Figure 4.3). Consequently, farmers’ net income declined to IDR 2,000,000–IDR 6,500,000 per month, depending on initial production levels. This decline aligns with the findings of Nurhayati et al. (2019), who reported that oil contamination can damage soil structure and reduce the availability of essential nutrients for plants. Pratama and Sari (2021) also noted that oil exposure on soil surfaces can trigger physiological stress in oil palm trees, thereby inhibiting the formation of fresh fruit bunches. Furthermore, Lestari (2023) emphasized that damage to soil microorganisms due to oil contamination contributes to reduced plantation productivity.

Economically, the decline in oil palm production represents a significant issue for farmers, particularly those who rely on plantations as their primary source of income. Although total income is not entirely lost, the reduction in monthly earnings is still substantial. This condition may affect household economic stability, especially in communities with limited income diversification (Hassan & Widodo, 2020; Rahmadani & Yusuf, 2022). Moreover, the recovery of oil-contaminated land can take months to years, requiring farmers to endure prolonged periods of reduced productivity. Thus, the impact of oil spills is not only ecological but also extends to significant economic and social consequences. Land restoration efforts—such as bioremediation, the addition of organic matter, and the restoration of soil microorganism populations—are essential steps to restore the productivity of oil palm plantations in affected areas (Sutrisno & Ardiansyah, 2024).

#### 4.3 Groundwater Quality at the PKM 15,800 Lukut Location

**Table 5.** Results of Groundwater Sample Analysis at the PKM 15,800 Lukut Location

Analyzed parameters	Method	Laboratory sample ID sampling Date/Time		Sumur Upstream 1 (SPU-1)	Downstream Well 1 (SPD-1)	Downstream Monitoring Well 1 (SPD-2)	Residents' homes
		LOR	Unit				
<b>Monitoring Year 2022</b>							
<b>Total Petroleum Hydrocarbon (C10-C36)</b>	USEPA Method 8015D, 2003	<b>100</b>	$\mu g/L$	<b>114</b>	<b>&lt;100</b>	<b>&lt;100</b>	-
<b>Total Petroleum Hydrocarbon (C10-C36)</b>	USEPA Method 8015D, 2003	<b>250</b>	$\mu g/L$	-	-	-	-

<b>Total Petroleum Hydrocarbon (C6-C9)</b>	USEPA Method 8260D, 2018	<b>50</b>	$\mu g/L$	<b>&lt;50</b>	<b>&lt;50</b>	<b>&lt;50</b>	-
<b>Monitoring Year 2023</b>							
<b>Total Petroleum Hydrocarbon (C10-C36)</b>	USEPA Method 8015D, 2003	<b>100</b>	$\mu g/L$	<b>&lt;100</b>	<b>&lt;100</b>	<b>&lt;100</b>	-
<b>Total Petroleum Hydrocarbon (C10-C36)</b>	USEPA Method 8015D, 2003	<b>250</b>	$\mu g/L$	-	-	-	-
<b>Total Petroleum Hydrocarbon (C6-C9)</b>	USEPA Method 8260D, 2018	<b>50</b>	$\mu g/L$	<b>&lt;50</b>	<b>&lt;50</b>	<b>&lt;50</b>	-
<b>Monitoring Year 2025</b>							
<b>Total Petroleum Hydrocarbon (C10-C36)</b>	USEPA Method 8015D, 2003	<b>100</b>	$\mu g/L$	<b>&lt;100</b>	<b>&lt;100</b>	<b>&lt;100</b>	-
<b>Total Petroleum Hydrocarbon (C10-C36)</b>	USEPA Method 8015D, 2003	<b>250</b>	$\mu g/L$	-	-	-	<b>&lt;250</b>
<b>Total Petroleum Hydrocarbon (C6-C9)</b>	USEPA Method 8260D, 2018	<b>50</b>	$\mu g/L$	<b>&lt;50</b>	<b>&lt;50</b>	<b>&lt;50</b>	<b>&lt;50</b>

Based on the results of the 2022 monitoring, the concentration of TPH of the C10–C36 fraction in Upstream Well 1 (SPU-1) was recorded at 114  $\mu g/L$ , which exceeded the quality standard of 100  $\mu g/L$  but was still below the threshold of 250  $\mu g/L$ . Meanwhile, in Downstream Well 1 (SPD-1) and Downstream Monitoring Well 2 (SPD-2), the TPH concentration of the C10–C36 fraction was below the detection limit (<100  $\mu g/L$ ). This condition indicates that in that period there are still heavy hydrocarbon residues in the upstream area, which is suspected to be related to the residual impact of petroleum spills or historical pollution accumulation around the source of oil and gas activities. This pattern is in line with the characteristics of heavy hydrocarbons that tend to accumulate near polluting sources and have relatively low mobility in groundwater media (Hoang *et al.*, 2021; ITRC, 2011).

Overall, the test results showed that the groundwater quality at the research site still met the environmental safety criteria based on the analyzed TPH parameters. Although the location has the potential to be exposed to oil and gas activities, the absence of TPH concentrations above the reporting limit indicates that there is no indication of hydrocarbon pollution that has an impact on the environment or public health at the time of monitoring.

#### 4.4 Groundwater Quality Monitoring and Management Strategy in Oil Contaminated Soil (TTM) Recovery Areas

**Table 6.** Analysis of Internal Strategy Factors

No	Internal Factors	Weight	Rating	Shoes
<b>Strength</b>				
1	The resources that exist in the community to overcome the problem of oil contamination are Oil Spill Contamination	0,09	2,00	0,18
2	Community groups or organizations that are active in environmental conservation efforts	0,12	3,00	0,37
3	Community knowledge in remediation efforts	0,08	1,00	0,08
4	Influential community leaders or informal leaders who can be agents of change	0,08	2,00	0,17
5	Local natural resources that can be used in the remediation process	0,09	1,00	0,09
6	Infrastructure that can support groundwater quality monitoring and management activities	0,09	3,00	0,26
<b>Total</b>				<b>1,14</b>
<b>Weakness</b>				
7	Obstacles or obstacles faced in an effort to overcome this oil contamination problem	0,08	2,00	0,16
8	Lack of public information or knowledge about the issue	0,06	2,00	0,13
9	Communities have economic limitations in accessing clean water or the technology needed for remediation	0,06	2,00	0,12
10	Community dependence on contaminated resources	0,06	2,00	0,13
11	Community beliefs or habits that are obstacles in efforts to change behavior	0,10	2,00	0,20
12	Conflict of interest between various interested parties	0,09	2,00	0,18
<b>Total</b>				<b>1,00</b>
<b>Differences</b>				<b>0,23</b>

**Table 7.** Analysis of External Strategy Factors

No	External Factors	Weight	Rating	Shoes
<b>Peluang (Opportunity)</b>				
1	Opportunities that can be leveraged to improve groundwater quality and the environment in this area	0,09	3,00	0,26
2	Support from the government or the private sector to address this problem?	0,10	3,00	0,30
3	Government policies that support environmental protection and public health efforts	0,10	3,00	0,29
4	Government programs that can be used to support remediation activities	0,10	3,00	0,29
5	An opportunity to attract investment in environmentally friendly economic activities?	0,10	3,00	0,31

<b>6</b>	Potential collaboration with research institutions, universities, or NGOs to develop relevant technologies or programs	0,10	1,00	0,10
<b>Total</b>				<b>1,54</b>
<b>Threat</b>				
<b>7</b>	Threats that can worsen environmental conditions due to oil contamination	0,06	1,00	0,06
<b>8</b>	Human activities that can exacerbate the oil contamination problem	0,08	1,00	0,08
<b>9</b>	The threat of natural disasters (floods, earthquakes) that can exacerbate contamination conditions	0,08	1,00	0,08
<b>10</b>	Climate change that can affect the remediation process	0,07	4,00	0,29
<b>11</b>	Human activities that have the potential to cause re-pollution (e.g., illegal waste disposal)	0,06	1,00	0,06
<b>12</b>	Population growth leads to increased pressure on water resources	0,06	1,00	0,06
<b>Total</b>		<b>1,00</b>		<b>0,66</b>
<b>Differences</b>				<b>0,91</b>

Based on the results of the SWOT matrix analysis, several key strategies can be formulated to optimize the internal strengths of the community by leveraging external opportunities in efforts to restore environmental quality, particularly groundwater in areas affected by oil contamination. First, integrating community resource capacity with environmental program opportunities. Strengths in the form of available community resources—such as manpower, local experience, and understanding of environmental conditions—can be optimized through the utilization of various government programs and environmental initiatives. This integration enables more effective mitigation and remediation implementation and accelerates groundwater quality recovery (Dwidjono, 2020; Ministry of Environment and Forestry, 2021).

Second, strengthening the active role of community groups and environmental organizations by utilizing support from government and the private sector as sources of funding and capacity building. This step is important to expand the scope of monitoring, improve the quality of interventions, and strengthen environmental institutions at the local level. This approach aligns with findings that collaboration between communities and government can significantly enhance environmental governance (Fitriyani & Nugroho, 2019).

Third, encouraging the use of local knowledge in the implementation of environmental protection policies. Community knowledge regarding soil characteristics, water sources, and contamination patterns can serve as a valuable scientific basis for policy implementation. This will strengthen groundwater governance and improve the effectiveness of pollution control programs in affected areas (Satria, 2020; Chambers, 2019).

Fourth, optimizing the role of community leaders as agents of change in environmental remediation and education programs. By leveraging their social legitimacy, the dissemination of information related to behavioral change, prevention of re-contamination, and the

importance of environmental monitoring can be conducted in a more persuasive and adaptive manner (Hidayat, 2022).

Fifth, maximizing the utilization of local natural resources and green investment to support remediation technologies, enabling the remediation process to be carried out more efficiently, in an environmentally friendly manner, and sustainably. This strategy also has the potential to drive local economic transformation toward more sustainability-oriented practices (UNEP, 2020).

Finally, the sixth strategy involves developing partnership networks among communities, universities, research institutions, and non-governmental organizations to strengthen remediation innovation. Local infrastructure support and accessibility can be leveraged to establish research and training collaborations with academic and non-governmental institutions. These partnerships aim to accelerate the development of remediation technologies, enhance community capacity, and expand the knowledge base in groundwater quality management (Astuti & Prasetyo, 2021).

## CONCLUSION

The petroleum spill in the PKM 15,800 Lukut area has been proven to impact ecological, social, and economic aspects. Ecologically, oil pollution disrupts the structure and function of ecosystems, as indicated by the predominance of tolerant pioneer vegetation, changes in the composition of flora and fauna, and signs of ecological succession in the early to intermediate recovery phase. From a social perspective, oil spills cause unrest, reduce the sense of security, and affect social interaction and cohesion, particularly among productive-age groups and households dependent on the agricultural sector. Economically, the most evident impact is observed in the oil palm plantation sector, where productivity and farmers' income have declined, although overall community economic activities have not completely ceased.

Groundwater quality at the PKM 15,800 Lukut location, following the removal of oil-contaminated soil, is generally in a safe condition based on Total Petroleum Hydrocarbon (TPH) parameters. Although heavy-fraction TPH residues were still detected at upstream points in 2022, continued monitoring through 2025 indicates that all monitoring wells show light and heavy TPH fraction concentrations below established quality standards and reporting limits. These findings suggest that the recovery efforts have been effective in reducing contamination levels, and that groundwater quality is currently stable and suitable for use, while still requiring periodic monitoring as a long-term precautionary measure.

The strategy for monitoring and managing groundwater quality in addressing oil spills at PKM 15,800 Lukut is best aligned with an aggressive (Strength–Opportunity) approach, supported by relatively strong internal factors (IFAS = 0.23) and substantial external opportunities (EFAS = 0.91). This strategy emphasizes optimizing internal capacities through the implementation of standardized and sustainable groundwater monitoring technologies, strengthening institutional frameworks and human resources, and leveraging regulatory support, multi-stakeholder collaboration, and community participation. Recovery efforts are directed not only toward controlling and preventing re-contamination but also toward

enhancing monitoring transparency, strengthening the role of communities and local leaders, and applying efficient and environmentally friendly remediation technologies.

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