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Regional Case Study

The Spatial Distribution of Petroleum Hydrocarbon Contamination in Groundwater Around Fuel Storage Tank

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Abstract

Groundwater is vital for domestic, agricultural, and industrial use; however, previous studies have indicated that its quality often fails to meet drinking water standards. The sources of groundwater contaminants can be from domestic, industrial, saltwater intrusion, surface waste ponds, pipelines, mine pits, underground storage tanks, waste pits, etc. This research investigates the spatial distribution of Total Petroleum Hydrocarbons (TPH) contamination in groundwater surrounding fuel storage tanks, using the LeGrand method to assess groundwater vulnerability based on five physical environmental parameters. The study employs a quantitative approach, incorporating primary data from well measurements and secondary data from geological and land use maps. The results reveal that shallow groundwater levels significantly increase vulnerability to contamination, while the type of soil and aquifer permeability also play critical roles in contaminant transport dynamics. In the second research location, the analysis focuses on benzene contamination, with low concentrations below 0.02 ppb. Despite the low levels detected, the potential for contamination remains a concern due to the proximity of the gas station to residential areas. Statistical correlation analysis demonstrates a significant inverse relationship between TPH concentrations and vulnerability scores. The study underscores the importance of preventive measures to mitigate contamination risks, involving collaboration among stakeholders.

Keywords: Benzene; groundwater contamination; groundwater vulnerability; legrand; spatial distribution; total petroleum hydrocarbon

1. Introduction

Groundwater is one of the clean water resources for domestic, agricultural, and industrial purposes in Yogyakarta Province. According to previous research, the groundwater quality in Yogyakarta does not meet the drinking water quality standard (Wijayanti et al., 2018). The sources of groundwater contaminants can be from domestic, industrial, saltwater intrusion, surface waste ponds, pipelines, mine pits, underground storage tanks, waste pits, etc. (Rahmawati et al., 2018; Utami et al., 2018). Contaminants like toxic metals, hydrocarbons, trace organic pollutants, pesticides, nanoparticles, microplastics, and other emerging pollutants pose a risk to human health, ecological functions, and sustainable socioeconomic growth (Al-Hashimi et al., 2021; Li et al., 2021).

Fuel storage tanks from gas stations and fuel terminal units have the potential to leak and contaminate groundwater (Emaanuel, 2022). Storage tank leaks can cause the contaminants to run into groundwater. Groundwater is the water-saturated layer underneath the soil. Aquifer conditions include land cover, rock type, aquifer type, and the topography of the aquifer area (Fei-Baffoe et al., 2024). Hydrocarbon can pollute the environment down to the sub-surface areas and aquifer layers of the soil. Besides that, it can also degrade the soil structure and is dangerous to human health due to its reactive, mutagenic, and toxic nature (Setianingsih & Titah, 2020).

The condition of pollutants in the aquifer will always be dynamic. This water mass will move the contaminant particles contained in the groundwater. The contaminant transport process in groundwater needs to be considered to determine the direction of the contaminant pollution (Notodarmojo, 2005). Organic pollutants such as Petroleum Hydrocarbon (PH) remain as the major class of pollutants of groundwater around the world. Due to their lower gravity than water, PH soon after a spill forms a pool of non-aqueous phase liquid (NAPL) of which, portion of NAPL gets dissolved slowly in groundwater resulting in a plume of hydrocarbons in the flowing groundwater. The contaminant can transfer from the pollution source to the groundwater. Furthermore, it can also be transported to the river, which acts as a gaining stream. Then, it can be easily moved when the groundwater-pumping rate increases because of the velocity value increase (Widada et al., 2017).

The first location of the research area is the Rewulu fuel oil terminal. The Rewulu fuel oil terminal is one of the places to store fuel in enormous quantities. Cases of fuel storage tank leaks have occurred in several countries such as at the Kallo fuel terminal, Belgium (October 25, 2005) which was caused by corrosion on the tank wall which caused the bottom wall of the tank to crack, a similar case also occurred at the fuel oil Terminal in Ambes, France in 2007 (Fei-Baffoe et al., 2024). Cases of gas station storage tank leaks can occur at any time in the future.

The second research area took place at Candimas Cilacap gas station. There has been a case of a storage tank leak at that location. The area around the gas station is a densely populated settlement that still uses dug wells as a source of water to meet daily needs, so that it has an impact on the socio-economy if a storage tank leak occurs. Determining the distribution of potential groundwater pollution by benzene from the source point to groundwater is the topic of the research problem being carried out. The Candimas Cilacap gas station storage tank as a source of pollution is located below the ground surface.

Based on vulnerability value and concentration, the spatial distribution of hydrocarbon contaminants in the groundwater will determine the contaminant pathways. This research objective is to determine the spatial distribution of Total Petroleum Hydrocarbon (TPH) contamination in groundwater around the fuel storage tank. The results of this research can be implemented as consideration to prevent and manage oil contamination from the fuel storage tank.

2. Methods

The research method is quantitative. LeGrand is used to determine groundwater vulnerability from TPH contamination. LeGrand method considers five environmental factors as the main data. Hydrocarbon concentration is used as support data for spatial distribution mapping. LeGrand's parameters to indicate vulnerability are the groundwater depth, the horizontal distance of the well with the contaminant sources, the map contour of groundwater table elevation, and flow nets. The secondary data required for this research are the map of soil type at Centre Jawa Province, well drilling map, and land use map of Centre Java Province.

Primary data collection was carried out by measuring the height of the groundwater table to obtain groundwater table height data so as to obtain flow nets. The assessment, scoring, and mapping of the depth of the groundwater table, absorption capacity above the groundwater table, aquifer permeability, slope of the groundwater table, and horizontal distance of the well to the source of pollution. The fluctuation of total scores of the five factors obtained as determinants of the potential for groundwater pollution (Maria & Rahmat, 2013). The distribution of groundwater pollution potential is adjusted to the direction of groundwater flow at the research location.

Groundwater table depth data was obtained using a meter and by directly measuring dug wells owned by the community. The depth data was used to determine the distribution of groundwater table height in the research area to create a groundwater table contour at the research location. The groundwater table height is calculated by comparing the height of the place above sea level (elevation) with the depth of the groundwater table.

The absorption capacity above the groundwater table is obtained by determining the soil texture with the interpretation of the absorption capacity above the groundwater table based on each sampling well by categorizing it into a soil series. Determination of soil texture takes into account the depth of the soil layer. The depth of the soil layer depends on the elevation point of the research object. The previously determined soil texture is analogous to the absorption capacity above the groundwater level.

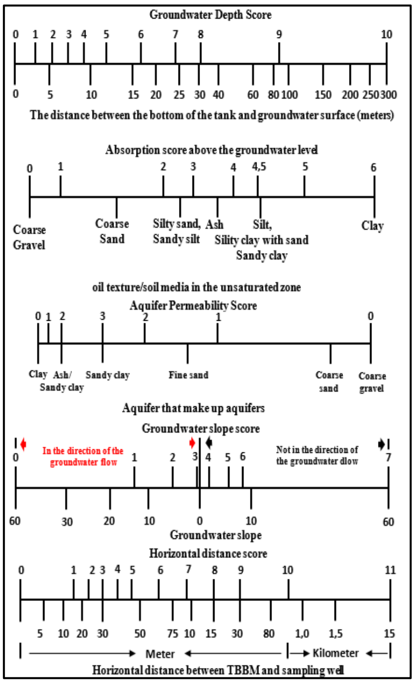

Figure 1. Scoring diagram of 5 environmental physical factors (LeGrand)

Measurement of aquifer permeability is determined based on the aquifer's constituent materials. The aquifer constituent materials obtained are based on the interpretation of well data obtained from around the research location. The determination of aquifer material is based on well interpretation, which considers the elevation of the well, the depth of the well, and the height of the groundwater level in each sampling well. The permeability value of each well is determined based on the aquifer constituent materials. The groundwater level slope (hydraulic gradient) is defined as the difference in the height of one groundwater level with another (Todd & Mays, 2004). The groundwater level can be calculated by interpreting the flow nets map. The following formula explains the percentage of groundwater level slope using equation (1):

$$i = \frac{dh}{ds} x \quad (1)$$

Description

i : groundwater level slope (%)

dh : change in groundwater level (m)
ds : horizontal distance between wells (m)

Determination of the horizontal distance of the well to the source of pollution is done by tracking GPS in the research area, then from the output of the elevation point and GPS location placed on the map using ArcGIS software so that the distance value is produced. Furthermore, scoring is carried out on each factor based on the diagram presented in Figure 1.

Determination of the potential pollution class is based on the total score of 5 physical environmental factors described in Table 1. The distribution of groundwater pollution potential is determined through the potential pollution class, groundwater flow direction, and hydrocarbon concentration.

Table 1. Total scoring value

No	Total Score	Potential Contamination Class
1.	0 - 4	Very High (very likely to be contaminated)
2.	4 – 8	High (can or may be contaminated)
3.	8 – 12	Moderate (may be contaminated but difficult)
4.	12 – 25	Low (very difficult to be contaminated)
5.	25 - 35	Very Low (almost unlikely to be contaminated)

Source: (Todd & Mays, 2004)

2.1. Evaluation of the Relationship between Quality and the Level of Groundwater Vulnerability

The analysis of the strength of the relationship between groundwater quality variables and vulnerability levels was conducted through statistical correlation analysis. The method employed was Spearmen Rank correlation analysis, which is used for nonparametric statistical correlation measurement (not requiring assumptions of normality and linearity) or ordinal scales. Data processing was carried out with statistics, and the results of the analysis were presented in a table containing the correlation coefficient values (rho/ρ) and significance values (sig.), which can subsequently be used to analyze whether a strong relationship exists between the studied variables. The higher correlation value (approaching 1), the stronger the relationship between the variables; conversely, the lower the correlation value (approaching 0), the weaker the relationship between the variables. The classification of the correlation coefficients can be seen in Table 2.

Table 2. Correlation coefficient category

Positive Rho	Negative Rho	Category
$0.9 \leq rho < 1$	$-0.9 \leq rho < -1$	Very strong
$0.7 \leq rho < 0.9$	$-0.7 \leq rho < -0.9$	Strong
$0.5 \leq rho < 0.7$	$-0.5 \leq rho < -0.7$	Moderate
$0.3 \leq rho < 0.5$	$-0.3 \leq rho < -0.5$	Weak
$0 \leq rho < 0.3$	$-0 \leq rho < -0.3$	Very weak

The groundwater quality parameters were compared with the quality standards outlined in the Special Region of Yogyakarta Governor Regulation No. 20 of 2008 for Class I water designated for drinking purposes and referenced previous research by regarding the threshold levels of TPH in groundwater (Monazami & Tehrani et al., 2014).

Table 3. Water quality parameter

Parameter	Highest Amount	
	Value	Unit
TPH*	0.6	mg/L
COD**	10	mg/L
TDS**	1000	mg/L

3. Results and Discussion

3.1. Groundwater Vulnerability Rate

3.1.1. Groundwater Vulnerability Value in Location 1

The vulnerability values of groundwater to potential contamination using the LeGrand method were obtained from assessing and scoring five physical environmental parameters. The assessment and scoring were conducted on 7 sample wells located at the research site. The potential contamination level of groundwater in Location 1 can be seen in Table 4. The data processing results indicate that a groundwater level of less than 5 meters has scores ranging from 0.1 to 1.88, indicating a higher vulnerability of groundwater to contamination at that location than a groundwater level greater than 5 meters, with scores exceeding 3. Shallow groundwater levels imply a shorter travel distance between surface contaminants and the groundwater, resulting in increased vulnerability to pollutants. Conversely, as the groundwater level becomes deeper, the travel distance for contaminants increases, leading to a reduced vulnerability.

Table 4. Potential level of groundwater pollution in the research area

Location	Groundwater Level Score	Absorption Score Above the Groundwater Level	Aquifer Permeability Score	Groundwater Level Slope Score	Horizontal Distance Score	Total Score	Potential Contamination Class
Point 1	3.80	4.6	0	3.20	9.49	21.09	Low
Point 2	1.80	4.6	0	3.20	10	19.68	Low
Point 3	1.61	4.6	0	3.10	10	19.31	Low
Point 4	0.99	4.6	0	3.20	8.96	16.86	Low
Point 5	1.57	4.6	0	5.08	8.83	20.08	Low
Point 6	1.04	4.6	0	5.10	8.63	19.37	Low
Point 7	3.38	4.6	0	3.24	8.33	19.55	Low

The absorption capacity above the groundwater table is influenced by the type of soil present above the aquifer, which is assessed through field observations of soil texture. This texture significantly affects both the soil's absorption capacity and the rate of water movement, thereby impacting contaminant transport. A single soil type with a clayey sandy texture was identified in the research area, scoring 4.6. According to Aller (1987), fine-textured materials like clay can reduce soil permeability, limiting contaminant transport, with smaller particle sizes generally correlating to lower contamination potential. The aquifer's permeability is determined by its constituent materials, as indicated by borehole logs obtained from the Public Works, Housing, and Mineral Resources. These reveal two distinct geological formations requiring separate logs. The first borehole consists of breccia with gravel-sized fragments and fine sand at depths of 3-8 meters, yielding a high transmission capacity score of 0. In contrast, the second borehole features limestone sand with medium-sized grains, resulting in a lower score of 0.

The slope of the groundwater table, calculated from the differences in water levels between wells, ranges from 0.12% to 1.57%, indicating a low flow velocity and vulnerability. Additionally, the horizontal distance from the contaminant source to the sample well, measured using ArcGIS, varies from 0.2 to 1.03 km, with the closest distance of 0.2 km suggesting a relatively low vulnerability, as indicated by the horizontal distance score nomogram, which shows high vulnerability at distances between 0-30 meters.

The five physical parameters utilized in the LeGrand method were processed using an overlay approach with Geographic Information System (GIS) technology, resulting in a total score ranging from 16.86 to 21.09, which indicates a low contamination potential class (very difficult to contaminate) and suggests that the vulnerability in the research area is relatively low. The distribution of groundwater vulnerability is illustrated in Figure 2. Key factors influencing contamination potential include aquifer permeability and groundwater table depth, with field observations showing that the aquifer material, consisting of gravel-sized breccia, has a score of 0, indicating high vulnerability. Additionally, the shallow groundwater depth significantly affects vulnerability levels. The low contamination potential is also influenced by the horizontal distance to the contaminant source; as this distance increases, the likelihood of contamination decreases due to factors such as dilution and natural degradation. Although the distance between the contaminant source and residents' wells is considerable, resulting in high scores (8.3 to 10), this does not imply the area is free from contamination, as other factors, including rainfall, can increase groundwater contamination potential by facilitating the transport of contaminants to the aquifer.

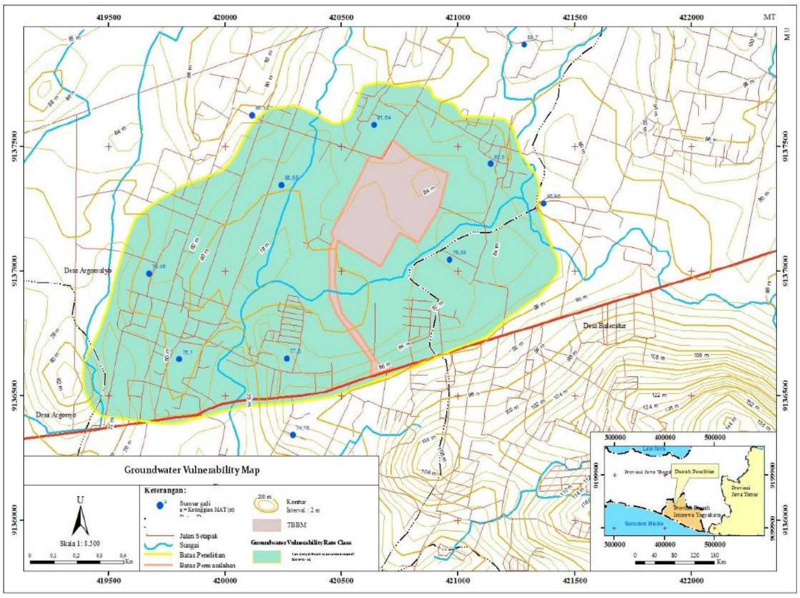

Figure 2. Groundwater vulnerability map (Location 1)

3.1.2. Groundwater Vulnerability Rate in Location 2

The study conducted at Location 2 investigates the contamination of groundwater by benzene. The potential for benzene contamination of groundwater at the research site was determined based on scoring of five physical environmental factors. These five factors were scored at 19 well locations within the study area. The study is near a gas station that potentially leaks benzene into groundwater.

The contamination potential distribution map indicates that the area most susceptible to contamination in the event of a leak is situated in the southern section of the gas station. The groundwater table within the study area is characterized by depths ranging from 3.73 to 7.63 meters, classifying it as shallow and near potential contamination sources. According to the groundwater table depth nomogram, this depth range is associated with a high-risk classification. Given that the contaminant source is located underground, the position of the groundwater table serves as a crucial natural parameter in assessing the potential for groundwater contamination; a decrease in the groundwater table height correlates with an increased likelihood of contamination (Shrestha et al., 2016).

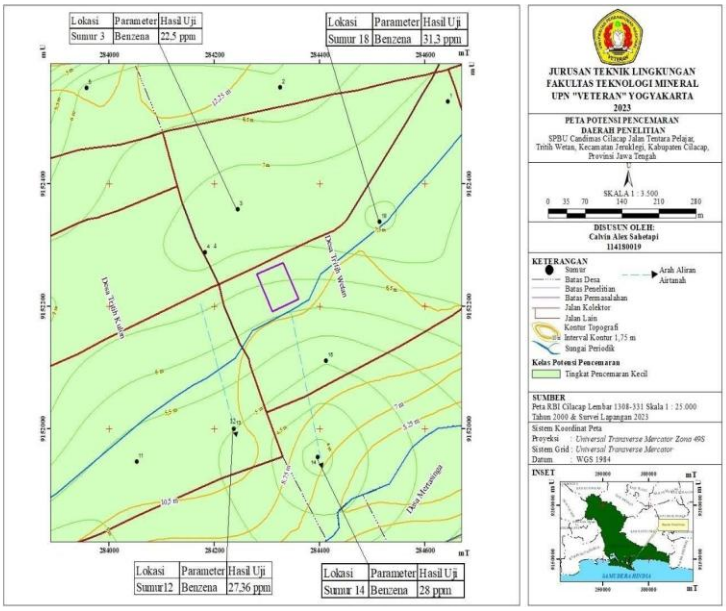

Figure 3. Potential groundwater contamination distribution map (Location 2)

The soil type map categorizes the study area as a sedimentary zone, predominantly characterized by a loamy sand texture with medium grain size, which may mitigate the potential for contamination. The texture of the soil is intrinsically linked to the underlying bedrock that constitutes the aquifer in this region. Based on geoelectrical analysis, the identified aquifer is composed of medium-sized sandstone, facilitating contaminant transport. A literature review indicates that the loamy sand texture in the study area yields a hydraulic conductivity value of 2.5 m/day, further influencing the movement of groundwater and potential contaminants.

The aquifer permeability coefficient quantifies the aquifer's capacity to transmit groundwater. LeGrand (1964) posits that aquifer permeability is contingent upon the size of the constituent materials, with smaller particle sizes resulting in lower permeability values. This permeability factor significantly impacts the potential for groundwater contamination from pollutants present at the research site, encompassing aspects such as permeability, infiltration capacity, absorption, and ion exchange (Alao, 2024). The slope of the groundwater table in the study area ranges from 0.02% to 1%, indicating a relatively gentle gradient. The transport of pollutants within the groundwater is influenced by both the direction of flow and the slope of the groundwater table; a gentler slope typically results in a reduced rate of pollutant transport. Additionally, field observations reveal that the horizontal distance from residential wells to the contamination source varies between 148.4 and 612.1 meters, suggesting a low potential for contamination in the event of a leak.

3.2. Relationship Between Vulnerability and Groundwater Quality

3.2.1. Groundwater Vulnerability and Quality in Location 1

The relationship between vulnerability levels and groundwater quality parameters was analyzed by processing the total pollution potential score data in conjunction with groundwater quality, specifically the concentrations of Total Petroleum Hydrocarbons (TPH), Chemical Oxygen Demand (COD), and Total Dissolved Solids (TDS) obtained from laboratory tests. The analysis of the relationships among the variables employed a nonparametric method, specifically the Spearman Rank method, which is appropriate given the ordinal nature of the data in this study. All four data variables are ordinal, indicating a ranking for both the vulnerability levels and the concentrations of TPH, COD, and TDS. The results of the groundwater quality tests are presented in Table 5. The results of the correlation analysis between groundwater quality and vulnerability levels, conducted using the Spearman Rank method with SPSS software, are presented in Table 6 below.

Table 5. Correlation coefficient category

Water Quality Parameters	Groundwater Sample							Water Quality Standards
	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	
TPH*	183	139	637	583	359	400	366	0,6 mg/L
COD*	66.37	116.37	83.03	66.36	116.36	119.70	76.36	10 mg/L
TDS**	412	196	372	403	552	382	508	1000 mg/L

Note : [orange box] Not suitable with Quality Standards

Table 6. Spearman rank method correlation analysis results

		Correlation		
		TPH	COD	TDS
Score	Correlation Coefficient	-0.857*	0.143	0. 393
	Sig. (2-tailed)	0.014	0.760	0.383
	N	7	7	7

3.2.2. Groundwater Vulnerability and Quality in Location 2

The results of laboratory tests for the presence of benzene concentrations in four groundwater samples from the research site are presented in Table 7. The benzene levels detected at the research site through the analysis of these four groundwater samples were not detectable, indicating relatively low concentrations, specifically below 0.02 ppb. This concentration remains below the quality standard threshold the Indonesian Ministry of Health set, which is 10 ppb. This finding is associated with the absence of any reported cases of underground storage tank leaks at the gas station, suggesting that environmental management efforts by the gas station, both technical and non-technical, have been practical. Additionally, benzene's volatile nature implies that only a small amount dissolves in water when it enters the environment.

Table 7. Results of benzene analysis on well water samples at the research location

Samples	Water Table Depth (m)	Temperature (°C)	Benzene Concentration (ppm)
Point 1	2.5	25	22.5
Point 2	1.07	25	31.3
Point 3	3.27	25	28
Point 4	3.5	25	27.36

The relationship between benzene concentrations and the potential for groundwater contamination at the research site was assessed through an analysis of the independent variable (benzene concentration) and the dependent variable (pollution potential score). The results indicated a linear and significant relationship, with a correlation coefficient (R) of 0.958 between pollution potential and benzene concentration. This value indicates a strong inverse relationship; as the benzene concentration in groundwater increases, the pollution potential score decreases, thereby indicating a greater potential for contamination. The presence of benzene in groundwater is generally attributed to the seepage from oil spills. Benzene is classified as a Light Non-Aqueous Phase Liquid (LNAPL), characterized as a colorless liquid with a distinctive odor that is insoluble in water and has a lower density than water (Rahman et al., 2019). Benzene can be detected in the air at concentrations ranging from 1.5 to 4.7 ppm, while in solution, it can be detected at concentrations of 0.5 to 4.5 ppm (U.S. Department of Health and Human Services, 2002).

4. Conclusions

At the first research site, the findings indicate that the vulnerability of groundwater to potential contamination is classified as low. Several key parameters, including the depth of the groundwater table, the absorption capacity above the groundwater table, aquifer permeability, the slope of the groundwater table, and the horizontal distance to potential contamination sources influence this classification. Furthermore, an analysis of the relationship between vulnerability scores and groundwater quality parameters—specifically Total Petroleum Hydrocarbons (TPH), Chemical Oxygen Demand (COD), and Total Dissolved Solids (TDS) was conducted using the Spearman Rank method. The results revealed a strong and significant inverse correlation between TPH concentrations and vulnerability scores, with a significance level of less than 0.05 and a correlation coefficient (ρ) of -0.857. Conversely, the parameters COD (ρ = 0.143) and TDS (ρ = 0.393) did not demonstrate significant relationships with vulnerability scores, as indicated by significance levels greater than 0.05.

The results of the second research location suggest that the area exhibits a low potential for groundwater contamination when evaluated based on physical environmental factors. Specifically, the findings indicate that the region south of the gas station is at risk of contamination in the event of a leak. The concentration of benzene in the groundwater at this site was found to be relatively low, measured at below 0.02 ppb, which is significantly below the quality standard threshold established by the Indonesian Ministry of Health, set at 10 ppb. Despite the low concentration, the potential for fuel contamination in the groundwater surrounding the gas station remains a concern, as it could adversely affect local residents whose wells may be impacted. Therefore, it is imperative to implement preventive measures to mitigate the risk of environmental contamination associated with the operation of the gas station in close proximity to residential areas. Key stakeholders in this effort include gas station management, operational staff, local government representatives focused on environmental impact mitigation, consumers, and nearby residents.

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