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Highly efficient in-situ remediation of total petroleum hydrocarbon via surfactant injection in contaminated groundwater

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ABSTRACT

Groundwater contamination by total petroleum hydrocarbons (TPH) represents a severe environmental and public health challenge, particularly in suburban areas of Java Island, Indonesia. This study assessed leakage from a fuel storage tank that resulted in widespread contamination of residential wells, with concentrations reaching up to 8024 mg/L. This result surpasses international regulatory limits. To address this issue, an in situ remediation approach was implemented by injecting the surfactant Tween 80 into five contaminated wells (GW1-GW5). Within 7 months of monitoring, this method achieved 85.5–100% TPH removal in contaminated wells, confirming its effectiveness for field-scale groundwater restoration. In addition, geophysical testing using the Automatic Audio-Frequency Magnetotelluric (ADMT) method confirmed persistent contamination at GW4, where low resistivity values revealed subsurface heterogeneity and basin effects that chemical monitoring alone could not explain. Moreover, the integration of ADMT with chemical monitoring demonstrated its effectiveness not only for aquifer exploration but also as a validation tool for contaminated soil remediation. These findings highlight the urgency of addressing petroleum hydrocarbon pollution and underscore the potential of surfactant injection, supported by geophysical monitoring, as a scalable and sustainable strategy for groundwater remediation in complex geological settings.

Keywords: ADMT, groundwater, surfactant injection, remediation, and TPH.

INTRODUCTION

Petroleum-based products are the primary source of energy for industry and everyday life worldwide. In contemporary society, petroleum products such as gasoline, diesel, and lubricants are used in greater quantities than other environmentally concerning chemicals (Logeshwaran et al., 2018). Petroleum-based products are released into the environment through accidents, leaks, and spills that occur during fuel exploration, production, transportation, and storage (Das and Chandran, 2011; Logeshwaran et al., 2018). Petroleum hydrocarbons percolate through soil columns and, due to their low octanol-water coefficient, ultimately render groundwater aquifers toxic. Even a small leakage rate of two drops per second can contaminate nearly half a billion gallons of water, rendering it unfit for drinking due to odor and taste issues (Fei-Baffoe et al., 2024). Environmental assessment of petroleum hydrocarbons is commonly conducted using analytical methods that quantify mineral oil content, reported as total petroleum hydrocarbons (TPH). The internationally accepted Standard ISO 16703, along with other methods, is applied to estimate TPH concentrations in the C10-C40 range (ISO 16703:2004, 2004). Other than TPH concentration, groundwater is considered contaminated when its physicochemical properties exceed the standards set by regulatory bodies such as the Environmental Protection Agency (EPA), Federal Environmental Protection Agency (FEPA), and World Health Organization (WHO), which may pose serious health risks (Oladimarun, 2025; USEPA, 2002). The EPA warns that the release of TPH poses serious risks to public health and safety by contaminating drinking water, increasing the risk of fire and explosion hazards, degrading air and water quality, endangering agriculture, damaging recreational areas and habitats, reducing food supplies, and depleting non-renewable resources (Adipah, 2019; Hosseini et al., 2023).

To ensure the evidence of contamination at the sites, comprehensive subsurface characterization methods are required. The Automatic Audio-Frequency Magnetotelluric (ADMT) system is essential to identify fractures and weathered layers that serve as primary pathways for contaminant migration. A study conducted in Tamil Nadu, India, demonstrated the effectiveness of ADMT in providing detailed subsurface lithological and structural information to depths of up to 300 m, thereby enabling accurate remediation site selection and reducing borehole failures (Sundaramoorthy et al., 2022). The study confirmed that the ADMT 300S can delineate aquifer-bearing fractures and weathered zones critical for groundwater remediation. Similarly, research in Ile-Ife, Nigeria, highlighted that the ADMT-200S effectively identified resistivity anomalies associated with water-saturated zones and, when integrated with borehole and topographic data, allowed prediction of contaminant plume migration pathways (Oluwadare et al., 2025).

Mitigating the spread of pollutants, maintaining environmental quality, and rapid remediation are required to protect the local community. Accordingly, in this study, in situ remediation was selected due to extensive TPH contamination and the need to reduce mobilization costs. According to Rewind (2020), which compares in-situ and ex-situ approaches, several technologies were evaluated for their applicability to the Java Island cases in Indonesia. Among those options, Surfactant Injection was prioritized for its efficient mobilization and recovery of hydrocarbons in complex subsurface settings, particularly in the presence of widespread contamination. As noted in the Rewind (2020), technology selection must consider contaminant phase distribution (adsorbed, dissolved, volatile, and Non-Aqueous Phase Liquid (NAPL)), site hydrogeology, and the balance between technical feasibility and environmental sustainability. Laboratory and field studies demonstrate that surfactant injection remediation significantly improves hydrocarbon removal efficiency in soil and groundwater by reducing tailing and rebound effects and increasing contaminant bioavailability (Balseiro-Romero et al., 2018; Cheng et al., 2017; Fleifel et al., 2020). Consistent with international best practices, these findings support the feasibility of surfactant injection for addressing widespread TPH contamination in aquifers (Liu et al., 2021). Alternative technologies from the screening matrix, including air sparging, bioslurping, and hydrofracturing enhancements, were not selected due to their limited effectiveness under specific site conditions (e.g., high soil permeability or localized contamination). Also, it would not adequately address the observed scale of TPH contamination. Although technically feasible, chemical oxidation and dual phase extraction were not selected due to their higher operational complexity and cost. These factors make widespread TPH remediation less efficient. Lastly, thermal treatment and in-well air stripping were excluded due to limited applicability, higher energy requirements, and reduced reliability (Rewind, 2020).

Both field and laboratory studies have verified the effectiveness of surfactant injection in groundwater remediation. For instance, a pilot study in South Korea achieved 88% TPH removal (48 kg) using sorbitan monooleate. Furthermore, contaminant extraction rates were up to 200 times higher than those achieved with conventional water flushing. Similarly, aquifer core experiments demonstrated 20 vol% crude oil removal with surfactant injection, while groundwater circulation well trials reduced naphthalene concentrations from 1.82 mg/L to 0.69 mg/L, effectively suppressing tailing and rebound effects (Liu et al., 2021). Taken together, these findings highlight surfactant injection remediation as a scalable and efficient strategy for managing widespread hydrocarbon contamination, supporting its adoption in both local and international groundwater management frameworks. This research specifically used Tween 80 as the surfactant for injection. Tween

80 has been widely validated as an effective surfactant for aquifer remediation, demonstrating strong performance in both laboratory and field applications. Laboratory column studies showed that flushing with Tween 80 achieved up to 81.5% removal of phenanthrene (a polycyclic aromatic hydrocarbon) within 12 hours, a significant improvement over systems without surfactant addition. More importantly, Tween 80 has proven successful under complex field conditions, including the removal of 92.5% of jet oil in Incheon, Korea, 53.9% of xylene in Gyeonggi-do, and 94–99% recovery of perchloroethylene (PCE) in a pilot-scale demonstration in Michigan, USA (Huo et al., 2020). These results highlight not only its efficiency across different contaminants but also its adaptability to diverse geological environments.

The consistent success of Tween 80 in real-world remediation projects underscores its reliability and makes it a preferred choice for practical implementation, offering both technical effectiveness and proven field applicability. However, most previous studies have been limited to laboratory trials or small pilot tests, often neglecting long-term monitoring under complex geological conditions. Few have integrated geophysical methods, such as ADMT, with chemical analysis to validate remediation success at the field scale.

This study aims to address the urgent need for in situ monitoring and remediation of petroleum hydrocarbons in groundwater. International regulatory frameworks highlight the severity of this issue. Nigeria's Environmental Guidelines and Standards for the Petroleum Industry (EGASPIN, 2002) set a maximum limit of 0.6 mg/L for TPH, the USEPA (2005) proposed effluent limitation of 5.0 mg/L as a maximum value, Australia's National Environmental Protection Council (Young and Tarnowy, 2022) sets limits of 1 mg/L for fractions C6–C10 and C10–C16, and New Zealand's (Ministry for The Environment, 2011) allows ranges of 0.59–5.2 mg/L for fraction C7–C9 and 1.4–9.2 mg/L for fraction C10–C14. These strict regulations reflect global awareness of the risks posed by petroleum hydrocarbons, which can contaminate soil and groundwater and accumulate as toxic residues. Within this regulatory context, this study evaluates advanced groundwater recovery approaches for TPH-contaminated residential wells, positioning them as viable remediation options to ensure the sustainability and safety of water resources.

This study also underscores the importance of addressing groundwater contamination within the framework of the sustainable development goals (SDGs). It contributes to SDG 6: Clean Water and Sanitation by restoring safe drinking water conditions for affected communities, and to SDG 15: Life on Land by supporting the remediation of terrestrial ecosystems impacted by petroleum pollution. Integrating geophysical monitoring with chemical analysis enhances remediation effectiveness while aligning with global sustainability targets for resilient water management and ecosystem health.

MATERIALS AND METHODS

Sample collection

Field observations were conducted by recording data, identifying and documenting the current conditions, and surveying the area (Figure 1). Groundwater contamination was assessed by collecting well water samples from residents' homes, following the procedures outlined in SNI 6989.58:2008, the Indonesian standard for groundwater sampling. A total of five contaminated well water samples (GW1-GW5) were collected for observation. Groundwater samples were collected from residential wells and assessed for TPH concentration. The method used for TPH concentration was Gravimetric EPA 1664A. The procedure begins with the collection of a minimum of 400 mL sample, which is then acidified to a pH below 2 using H_2SO_4. The sample was then extracted with n-hexane (in three 30 mL portions) using liquid-liquid extraction (LLE). The combined organic extracts were concentrated by evaporating the solvent at 85 °C in a water bath until dryness. The residue obtained is re-dissolved in fresh n-hexane and treated with silica gel to remove polar compounds. The treated extract is then weighed gravimetrically, and the result is reported as silica gel-treated n-hexane extractable material (SGT-HEM), representing the concentration of TPH (Adeniji et al., 2017; USEPA, 2005)as well as the nonpolar materials, has become a preferred choice, despite being not suitable for volatiles because of the mandatory evaporation step. Other frequently used methods include gas chromatography with a flame ionization detector (FID).

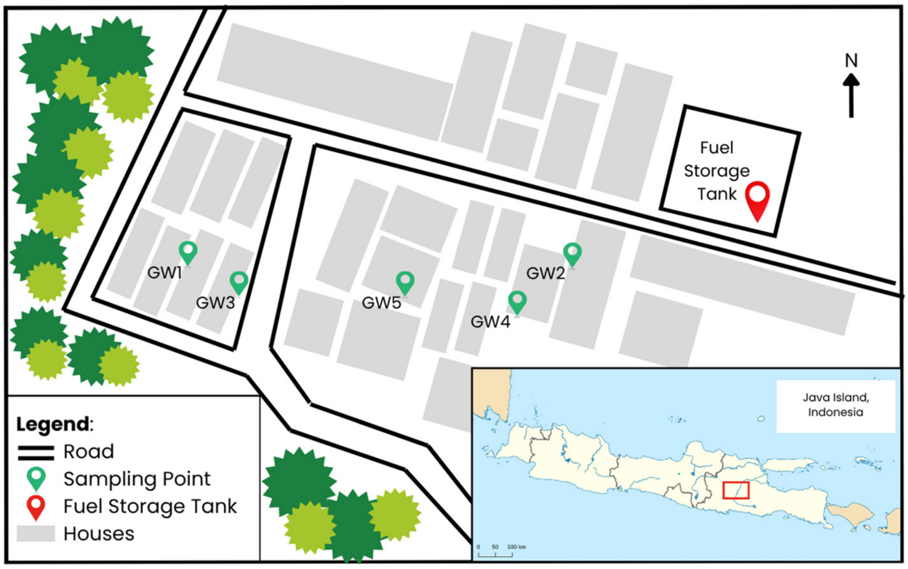

Figure 1. Groundwater sampling points in contaminated soil

Tween 80 surfactant injection

Prior to field application, the surfactant concentration was evaluated at the laboratory scale to determine the appropriate dosage. Technical-grade Tween 80 was selected as the surfactant (Figure 2). Artificial samples (200 mL) were prepared using distilled water spiked with petroleum products at 10% (v/v). Tween 80 was added to the samples at concentrations of 2.5%, 12.5%, 25%, and 50% (v/v), prepared from a 10% (v/v) stock solution. Visual observations were conducted daily over 28 days to assess changes in the samples. The optimal observation results were used as the reference to determine the surfactant injection concentration in the field. Surfactant injection was conducted in five groundwater wells (GW1–GW5). The amount introduced into each well was adjusted to match the respective water volumes. Monitoring of all five wells was conducted every 3 months for 7 months.

Geophysical testing

Geophysical testing was conducted to obtain spatially resolved information on subsurface conditions that cannot be derived from water sampling alone (Ahmad et al., 2025). In this study, ADMT surveys were focused on household wells with persistently high petroleum concentrations, as indicated by post-remediation TPH measurements. The objective of the geophysical ADMT survey was to characterize subsurface conditions surrounding the contaminated wells. Geophysical testing was performed using the ADMT 300S instrument (Aidu Energy Technology, China), which uses Earth's natural electromagnetic field as its data source. The ADMT system passively records electrical (E) and magnetic (B) components at the ground surface through non-polarizable electrodes. Measurements were carried out across a frequency range of 25 Hz to 30 kHz, enabling detection

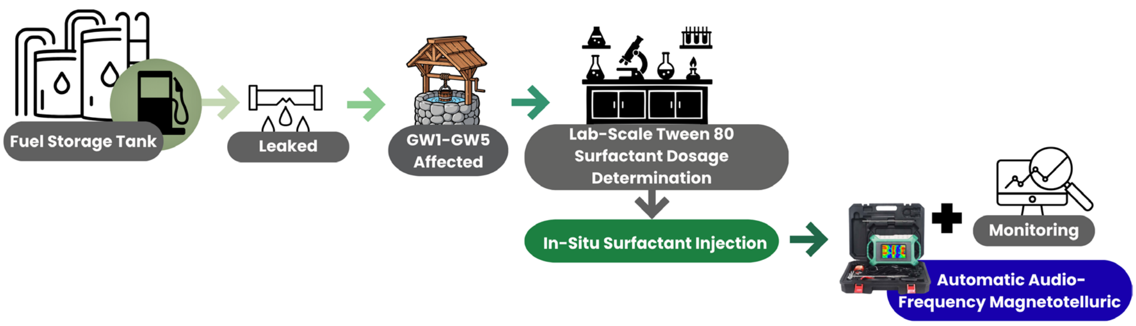

Figure 2. Remediation strategy

of subsurface resistivity variations (Ali et al., 2025). Field procedures typically began with electrode placement at 10 m intervals. The recorded data, expressed as electrical potential differences in millivolts (mV), were processed using the ADMT's built-in algorithms. The results were presented as two-dimensional apparent resistivity profiles with color spectra: blue indicating conductive zones (water-saturated layers or aquifers), and red indicating resistive zones (compact rock or laterite) (Figure 3). Concentrated contour lines were generally interpreted as fractures or faults with potential for groundwater storage.

RESULTS AND DISCUSSION

Indicative site observations suggested varying levels of TPH contamination across groundwater samples. To provide a representative estimate, the contamination percentage was set to 10%, reflecting the approximate proportion of petroleum hydrocarbons relative to the water volume under observed conditions. For example, if 1 m^3 of water (≈ 1,000,000 mL) contains approximately 100,000 mg of TPH, this can be interpreted as about 10% of the total volume being contaminated. Thus, the 10% figure does not represent the absolute volume of oil in water, but rather an estimated relative proportion of contaminants within the overall sample. The approach simplifies laboratory data interpretation and provides a quantitative perspective useful for remediation planning.

The laboratory experiments were conducted to determine the appropriate surfactant dosages. Observation showed that the initial addition of Tween 80 produced a milky-white turbidity in water, attributable to its soap-like properties. The required dosage for household well remediation was identified as 2.5 L Tween 80 per 1 m^3 of groundwater (2.5% v/v). This finding aligns with previous studies that reported that 1.5 mL of Tween 80 in a 100 mL solution (1.5% v/v) removed of 15% of diesel contamination in soil (Liu et al., 2022). Previous studies had reported that applying Tween 80 at concentrations of 1–5% (v/v) can achieve up to 70% removal of PAHs in standard solutions (Mirzaee, 2022). In laboratory trials conducted in this study, a 10% reduction in TPH in 200 mL of water required 5 mL of 10% Tween 80, with 5 days of monitoring to confirm droplet formation and molecular dispersion. Field application involved dosing five open household wells (GW1–GW5) based on water volume, during which floc formation was observed at the bottom, necessitating subsequent flushing to remove sediment and residues (Figure 4).

After surfactant was injected at the five sampling points (GW1-GW5), monitoring was conducted at all locations over seven months. Tween 80 (polysorbate 80) is a nonionic surfactant that reduces the surface tension between two liquids.

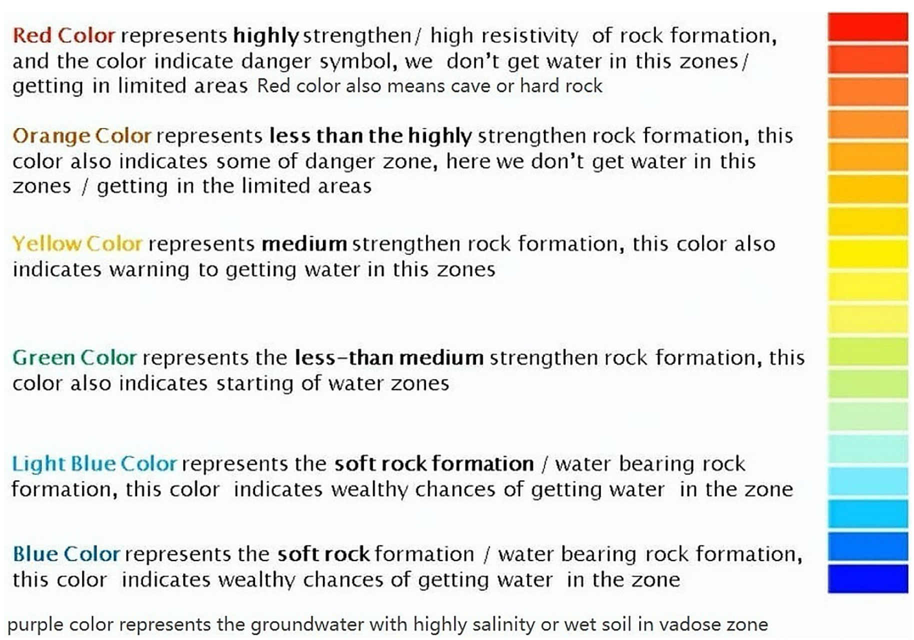

Figure 3. Color spectrum of ADMT measurement data modeling (Aidu Energy Technology, 2020)

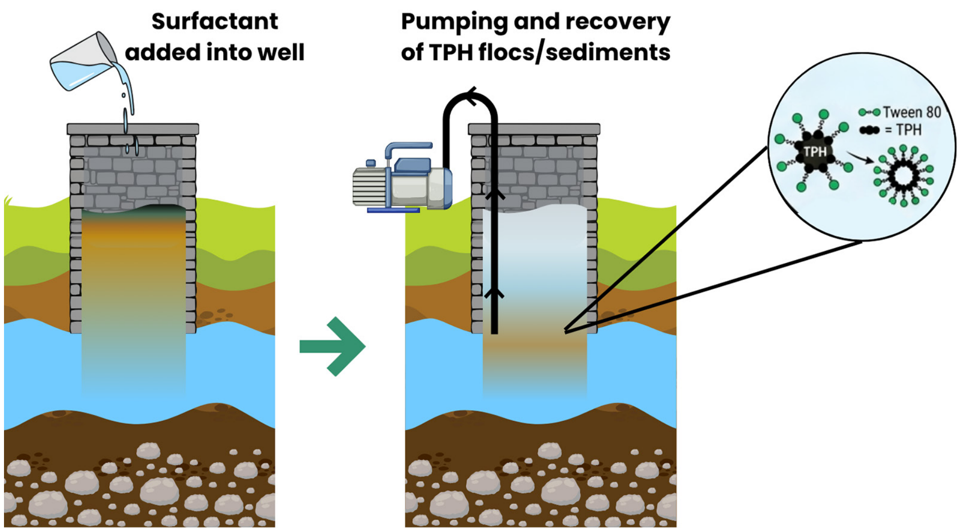

Figure 4. Surfactant injection mechanism in groundwater remediation

Surfactant is selected due to its proper performance for in-well TPH remediation, lower interfacial tension, and increased hydrocarbon solubility while exhibiting relatively low ecological risk (Cheng et al., 2018). Mechanistically, the critical micelle concentration (CMC) of Tween 80 defines the micelle size that solubilizes hydrophobic petroleum fractions. In contrast, at or below sub-CMC levels, monomeric surfactant enhances desorption at the solid–liquid interface (Petrova et al., 2025). In practice, injected Tween 80 disperses free-product oil into finer droplets (emulsification), transfers TPH into the aqueous/micellar phase (pseudo-solubilization), and promotes formation of flocs/settled material that can be recovered by pumping. The mobilized TPH is then more accessible to downstream treatments (physical separation, adsorption, biodegradation). Key operational considerations are dose optimization, monitoring surfactant residues and ecotoxicity, and managing recovered flocs/waste to prevent secondary contamination (Cheng et al., 2018; Petrova et al., 2025).

As shown in Figure 5, all well points exhibited declining TPH concentrations. Monitoring results showed that at three well points (GW1, GW2, and GW5), TPH was completely removed (100%), whereas at GW3 and GW4, residual TPH was retained at 1 mg/L and 44 mg/L, respectively. Over the first three months, TPH concentrations declined markedly across all monitoring wells: GW1 decreased from 4054 mg/L to 0 mg/L (100% removal); GW2 fell from 7920 mg/L to 275 mg/L (96.5% removal); GW3 dropped from 2464 mg/L to 6.5 mg/L (99.7% removal); GW4 decreased from 8024 mg/L to 1166.5 mg/L (85.5% removal); and GW5 fell from 2 mg/L to 0 mg/L (100% removal).

In the subsequent three months, further reductions were observed: GW2 reached 0 mg/L (100% removal from 275 mg/L), GW3 declined to 1 mg/L (84.6% removal from 6.5 mg/L), and GW4 declined to 44 mg/L (96.2% removal from 1166.5 mg/L). These results indicate rapid initial removal in most wells, with residual concentrations persisting only at GW3 and GW4 during the later monitoring period. After that, geophysical testing was carried out at GW4, which still exhibited high TPH concentrations, and at GW5 to serve as a comparison or control point. At GW4, the resistivity was the lowest, indicated by a purple color (2–8 Ωm), which was interpreted as evidence of petroleum contaminants in groundwater. The groundwater basin profile also revealed a sloping condition between depths of 5–25 meters (Figure 6). Analysis indicates that petroleum continues to saturate the well, consistent with water quality test results showing persistently high TPH concentrations even after remediation. The subsurface soil layers, deposited with uneven thicknesses, have formed a basin (at the lower position of GW4) located between GW2 and GW5 (Figure 1), which likely contributes to the accumulation of groundwater and petroleum contaminants. Because petroleum has a lower density than water, it tends to remain above the water table. When mixed with groundwater, petroleum accumulates at the surface and takes longer to disperse. In contrast, ADMT results at GW5 did not reveal the presence of contaminants, as indicated by the absence of

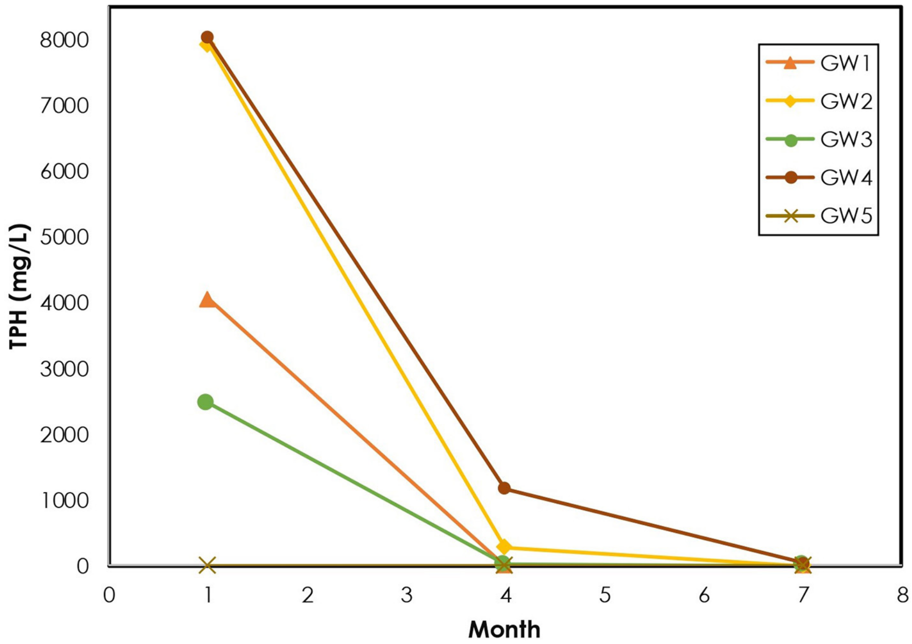

Figure 5. Trend of TPH concentration in GW1-GW5 in 7 months during the injection of surfactant

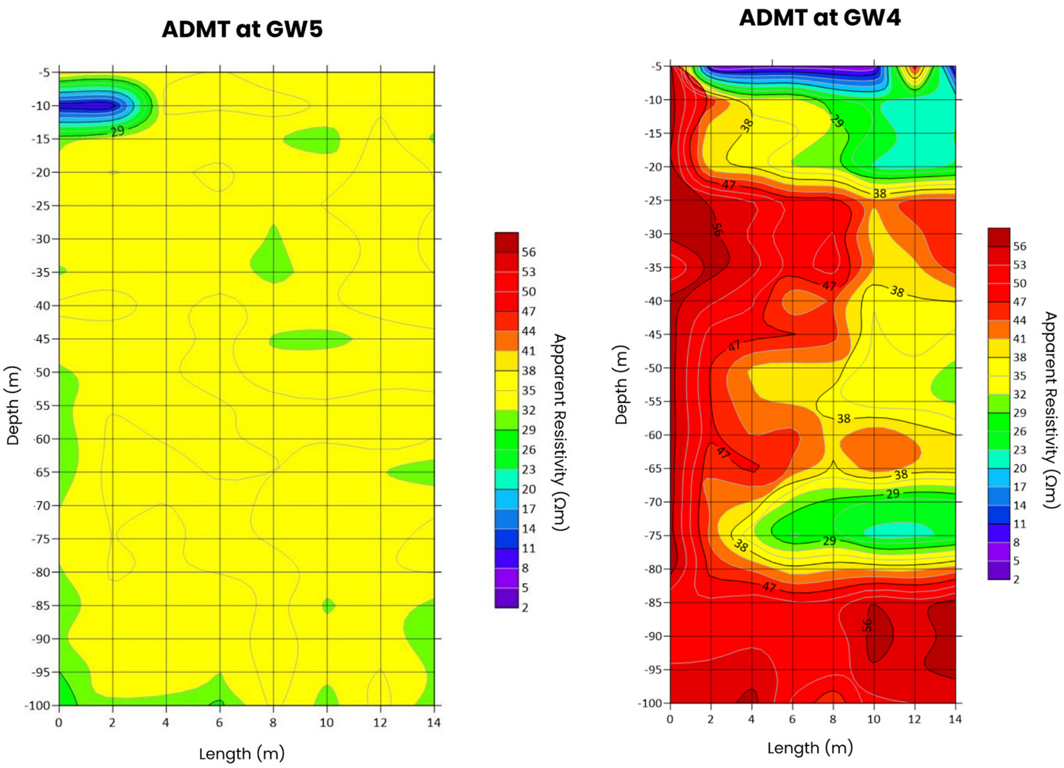

Figure 6. Results of ADMT geophysical survey data processing

low-resistivity values, consistent with TPH measurements showing complete removal (0 mg/L).

Regarding the result, GW5's oddly low TPH, compared to the other four, is plausibly explained by hydrogeological and well-construction factors rather than by analytical error. Wells that are not in the path of the pollution or that draw water from other sites, or that draw water from isolated layers, usually show much lower contaminant levels than wells located downstream of the plume. Long wells that sample multiple layers simultaneously can yield misleading results because water moves up and down within the well, and the sample reflects the average of the layers contributing to flow at that moment (Day-Lewis et al., 2024). Similarly, Gailey emphasizes that contaminant migration through inactive supply wells can negatively affect groundwater quality and that well-screen depth relative to hydrostratigraphy controls whether well samples are contaminated or clean zones (Gailey, 2018). Furthermore, these studies imply that GW5's low TPH likely reflects its screened interval and position relative to the contamination (e.g., up-to-date location, isolated screen, or connection to a cleaner recharge pathway). Mapping flow direction, comparing well-construction logs, and repeating low-flow sampling with QA/QC might address these limitations.

The persistence of TPH at GW4 highlights the influence of subsurface heterogeneity and basin geometry, consistent with findings from magnetotelluric surveys in Ghana, where fractured and weathered zones controlled groundwater occurrence but were highly sensitive to surface noise (Agyemang, 2022). The correlation observed between ADMT outcomes and chemical data reinforces ADMT's role not only as an aquifer exploration tool but also as a reliable means of validating remediation success, effectively identifying low-resistivity zones associated with hydrocarbon presence. This finding aligns with previous studies (Sundaramoorthy et al., 2022), which emphasized the critical role of ADMT in large-scale contamination cases where chemical monitoring alone often fails to capture contaminant distribution.

Tween-80 has been widely studied as a surfactant for the remediation of hydrophobic organic contaminants. Its advantages lie in the way it works, where at low concentrations, Tween-80 monomers accumulate at the solid–liquid interface, promoting desorption of hydrophobic organic compounds (HOCs) from soil particles. When the concentrations above the critical micelle concentration (CMC ≈ 13 $mg \cdot L^{-1}$), Tween-80 forms micelles whose hydrophobic cores strongly compete with soil particles, solubilizing HOCs and increasing their mobility and bioavailability for microbial degradation and plant uptake (Cheng et al., 2018). These mechanistic properties explain why Tween-80 enhances solubility and biodegradation, while also presenting challenges such as microbial shifts, mobilization of secondary pollutants, and reduced field efficiency compared to laboratory conditions (Cheng et al., 2017). Moreover, previous research reported that Tween-80 achieved ~71% biodegradability within 28 days and was classified as practically non-toxic (LC_{50} > 300 $mg \cdot L^{-1}$ in zebrafish), supporting its suitability for remediating hydrophobic organic contaminants (Nazar et al., 2022). Nevertheless, Tween-80 stimulates *Staphylococcus aureus* biofilm growth while reducing biofilm formation in *Listeria monocytogenes* and *Pseudomonas fluorescens*, and lowering the efficacy of hydrophobic antimicrobials (Nielsen et al., 2016).

These findings highlight both the promise and limitations of surfactant-based remediation: while such mixtures can be relatively effective and safe. Their performance depends on environmental factors and long-term persistence. Based on previous reports by authors (Caetano et al., 2024; Zhang & Zhu, 2012), avoiding excessive surfactant dosing because effectiveness is concentration-dependent. High doses promote micelle formation, which can reduce contaminant bioavailability to microbes and inhibit biodegradation. Surfactant choice should therefore balance extraction efficiency against toxicity. Additionally, a follow-up treatment strategy (e.g., activated carbon) is needed to prevent the release of surfactants and suspended contaminants.

For groundwater applications, these insights underscore the need for extended monitoring—combining chemical sampling with ADMT surveys over 12–24 months—to detect potential rebound and confirm long-term stability. Given that TPH concentrations at GW4 remain above EGASPIN and USEPA standards thresholds even after seven months. Further research is required to design and implement advanced, site-specific remediation strategies. One of the best recommendations for advanced groundwater remediation is the use of permeable reactive barriers (PRBs). PRBs provide clear advantages over conventional groundwater remediation methods, such as pump-and-treat, bioventing, or chemical oxidation, particularly in preventing plume migration and safeguarding sensitive areas. Well-designed PRB systems have been shown to reduce costs and sustain long-term performance. Nonetheless, some barriers fail to meet expectations due to factors such as inadequate reactive media, insufficient thickness or width, and declining porosity. Careful design is therefore essential to minimize these risks. At the study site (Ren et al., 2024), contaminants were concentrated at depths of 4–5 m below the surface. Given the low solubility of TPH and the unsaturated groundwater zone where the spill occurred, rainfall and gravity strongly influenced dispersion, with TPH forming a light non-aqueous phase liquid. These conditions further underscore the importance of PRBs as a containment strategy, ensuring that mobilized hydrocarbons are intercepted and treated before spreading further. Their main advantages are passive operation, extended service life, and the ability to couple adsorption with biodegradation. However, challenges remain, such as the need for precise design, geological heterogeneity, and the risk of reactive media clogging (Ren et al., 2024). Consequently, PRBs serve as a valuable follow-up strategy within a treatment-train approach, complementing surfactant injection by stabilizing mobilized contaminants and reducing the risk of rebound.

CONCLUSIONS

Our field-scale results provide direct evidence of the effectiveness of Tween 80 injection in Indonesian aquifers. Across five household wells, TPH concentrations declined by 85.5–100% within seven months, with complete removal achieved at GW1, GW2, and GW5. These outcomes, particularly the persistence of 44 mg/L at GW4 due to basin heterogeneity, highlight the importance of integrating geophysical monitoring with chemical analysis. Unlike prior laboratory-focused studies, our findings demonstrate practical challenges such as floc formation, sediment flushing, and rebound effects, offering site-specific insights into the scalability of surfactant injection for contaminated groundwater remediation.

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