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REVIEW

Reimagining Oil Spill Response: Innovations in Detection, Risk Assessment, and Sustainable Remediation Pathways

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ABSTRACT

A leaking refined-oil pipeline is a significant, but frequently overlooked, source of soil and groundwater contamination. The leakage from underground pipelines can be undetected for extended periods and can travel vertically through the vadose zone and horizontally in an aquifer, where gasoline, diesel, and associated petroleum hydrocarbons may accumulate. This review aims to compile existing understanding of detecting, migrating, assessing risk, and remediating a refined-oil pipeline contamination in a coupled soil groundwater system. Special attention is devoted to some of the most important pollutants, such as benzene, toluene, ethylbenzene, and xylenes (BTEX), polycyclic aromatic hydrocarbons, methyl tert-butyl ether, volatile petroleum hydrocarbons, and extractable petroleum hydrocarbons. The discussion highlights the fact that contamination in the upper layers of soil may not provide a reliable assessment of subsurface contamination, since unweathered residual petroleum can cause a prolonged secondary source of contamination to groundwater plumes. Contaminant transport and remediation feasibility are highly influenced by hydrogeological conditions, such as soil texture, fractures, loess structure, aquifer properties, and groundwater flow direction. While conventional remediation technologies can deliver quick risk reduction, integrated approaches that combine bioremediation, monitored natural attenuation, nature-based solutions, emerging treatment technologies, and long-term monitoring are increasingly required to ensure sustainable management. A representative pipeline leakage case (Luoyang–Zhumadian) is used throughout to illustrate key concepts, but the review synthesizes findings from

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multiple studies. The article proposes a proactive approach, one that moves beyond a reactive cleanup model to adaptive and predictive management, using intelligent monitoring, contaminant transport modelling, source-pathway-receptor analysis, and risk-based decision-making. The integrated approach can enhance protection of the environment, the effectiveness of remediation, and the security of groundwater resources in areas impacted by refined-oil pipeline spills.
Keywords: Refined-Oil Pipeline Leakage; Soil-Groundwater Contamination; Petroleum Hydrocarbons; Groundwater Plume; Sustainable Remediation

1. Introduction

Petroleum products are essential to today's energy systems, industry, transportation, and agriculture. Long-distance refined-oil pipelines are generally considered to be efficient and relatively safe infrastructure for transporting petroleum fuels [1]. After leakage, particularly from underground pipelines, refined oil products may travel undetected through the soil and groundwater systems. In contrast to oil spills that occur on the surface of streams, rivers, or marine water bodies, the occurrence of subsurface oil pipelines is more difficult to detect, delineate, and remediate because of the hidden source of pollution, the potential for long-term releases, and the extent to which site-specific geological and hydrogeological conditions control the migration of pollution. These properties render pipeline contamination the most challenging environmental issue facing the oil and/or gas industry of petroleum chemistry, hydrogeology, risk assessment, remediation engineering, and long-term environmental management [2,3].

In areas of agriculture and rural development, the environmental consequences of refined-oil pipeline leaks are especially pronounced because shallow depth, deep vadose zones, and groundwater resources are in a direct relationship with agricultural and rural food production, irrigation systems, and drinking water safety. Leaks in gasoline and diesel pipelines can release a variety of volatile, semi-volatile, soluble, and persistent pollutants into the subsurface environment. Common contaminants include benzene, toluene, ethylbenzene, xylene, naphthalene, methyl tert-butyl ether (MTBE), volatile petroleum hydrocarbons, and extractable petroleum hydrocarbons. The compounds have significant differences in volatility, solubility, sorption affinity, biodegradability, and toxicity, which give rise to their complex multi-phase migration and transformation. More soluble components, like MTBE and some BTEX chemicals, can travel for long distances with the groundwater, and less soluble petroleum components may be left behind as a residual contaminant and become long-term secondary sources. Thus, a refined-oil pipeline leak cannot be considered only a soil pollution problem, but a coupled soil–groundwater pollution problem with long-term environmental and health impacts [4,5].

The case of pollution to a refined-oil pipeline in central China is representative of these challenges. In 2009, illegal tapping of a buried refinedoil pipeline was discovered, and leaked gasoline and diesel slowly percolated through surrounding soils and contaminated groundwater. Visible oil contamination and petroleum odors were subsequently detected in nearby irrigation and drinking wells. This major investigation involved the collection of historical data, site visits, interviews, hydrogeological investigations, soil and groundwater sampling, drilling, laboratory analysis, and pollution risk assessment from November 2022 to February 2023. The investigation identified 109 locations for sampling soils and 23 locations for monitoring groundwater, showcasing the extent and complexity needed to properly define the extent of the impacts from buried pipeline leaks [6–8].

The case also exposes how much contamination of refined-oil pipelines can be underestimated using only surface observations. The investigation showed that the shallow soils in the agricultural areas were predominantly non-contaminated at levels of concern, with deeper soils in the vicinity of the leakage point showing high levels of petroleum contamination. The soil contamination extended downwards, creating an "umbrella-shaped" distribution around the leakage place. The groundwater contamination was more severe than the surface soil contamination and was present as a plume that extended eastward in the direction of regional groundwater flow. The estimated groundwater contamination zone was approximately 700 m long in the north–south direction and 1,500 m long in the east–west direction, with an area of approximately 0.77 km^2. The results show the significance of not only apparent surface-soil risk but also hidden deep subsurface risk in pipeline leakage assessment [9,10].

One of the important scientific questions concerning contamination events is the role of hydrogeological heterogeneity. In the study area, petroleum contaminants were allowed to migrate downward through the loess soils, pass through fractures, permeable layers, and percolate through the groundwater flow conditions to be transported horizontally through the groundwater-bearing formations. The report found that petroleum contaminants entered and percolated about 75 m into the soil prior to reaching the groundwater-bearing formations and that the nature of groundwater flow and the geological features in the area significantly affected the migration and persistence of the petroleum contaminants. This means that the behavior of contaminants cannot be fully understood based on the properties of the pollutant. In reality, the migration pathway, plume geometry, attenuation capacity, and remediation difficulty are all influenced by source characteristics, vadose-zone structure, aquifer characteristics, hydraulic gradients, and remediation biogeochemical transformations [11–13].

Although significant strides have been made in the technologies available to respond to an oil spill, there are still some areas of concern with regard to the management of leakage from refined-oil pipelines. Firstly, traditional leak detection techniques, such as delayed sampling, visual inspection, and pressure monitoring, might not be able to catch small or intermittent subsurface leaks in time. Secondly, site investigations are often piecemeal, with attention to pipeline integrity, soil contamination, and groundwater quality, but not to all three aspects as a whole system model. Third, many remedial actions are taken after the pollution has already infiltrated groundwater, adding to the cost and uncertainty of the remediation decision. Fourth, traditional remediation methods like excavation, pump and treat, containment, chemical oxidation, and soil vapor extraction may work in some situations, but can be costly, energy intensive, disruptive, or inadequate to address deep vadose-zone and long plumes. The constraints make review studies imperative, going beyond the general cleanup of oil spills and specifically focusing on leaks from refined-oil pipelines in coupled soil–groundwater systems [14,15].

There are new opportunities to improve pipeline leakage management that have emerged in recent years. Early warning and pollution detection can be enhanced using remote sensing, unmanned aerial vehicle (UAV) surveillance, ground-penetrating radar, electrical resistivity tomography, fiber-optic sensing, hydro geophysical monitoring, Internet of Things (IoT) sensor networks and artificial intelligence. The use of Geographic Information System (GIS)-based spatial analysis, numerical groundwater models, source–pathway–receptor frameworks, probabilistic risk assessment, and machine-learning-based prediction can enhance risk assessment and plume forecasting. In remediation, monitored natural attenuation, bioaugmentation, biostimulation, constructed wetlands, biochar amendments, electrokinetic, nanotechnology-assisted remediation, surfactant-enhanced recovery, and hybrid treatment systems are being given increased attention. The authors of the proposed review outline are particularly focused on this shift from a series of stand-alone response technologies to a continuum of detection, risk assessment, more sustainable remediation and adaptive management [16–19].

The novelty of this review is that it focuses on the leakage of refined oil as a deep soil–groundwater contamination system, as opposed to a typical surface oil spill or a typical petroleum-contaminated site. To ground this review in real-world complexity, we draw upon a representative refined-oil pipeline leakage case from central China (Luoyang–Zhumadian) as an illustrative example. This case is one of several informing the synthesis presented here. First, the deep vadose zone is the focus of this review, highlighting vertical migration, residual petroleum retention, delayed groundwater impact and secondary source behavior. Secondly, it identifies the potential for the development of groundwater plumes as a major environmental threat, particularly when soluble petroleum constituents are able to move away from the immediate point of leakage. Third, it uses hydrogeological controls to connect the chemistry of contaminants, highlighting the influence of soil texture, loess structure, fractures, aquifer properties, groundwater flow, and seasonal dynamics on pollutant migration and attenuation. Fourth, it brings together detection, monitoring, risk assessment, remediation, and post-remediation management under a single roof for refined-oil pipeline leakage response. This holistic approach is especially relevant because the success of any one technology relies on accurate identification of the sources, characterization of the pathways, identification of receptors, and monitoring of the plumes over time [20].

This review is also unique in bringing together, in a single context, case-based environmental investigation and next-generation management concepts. In the pipeline leakage case in central China, the leakage source has been removed, and concentrations of the contaminants have been slowly decreasing over a period of years, but the leakage continues in the subsurface. Emergency repair or short-term cleaning is not enough for such cases; they need adaptive management, which is based on continual monitoring, new risk assessment, and adaptive remediation. Thus, future pipeline leakage management should move from a reactive approach of 'detect, repair, and remediate' to a proactive and adaptive approach that involves the integration of intelligent monitoring, hydrogeological modelling, risk-based prioritisation, sustainable remediation and governance of the environment over the long term [21].

This review is intended to provide a synthesis of existing knowledge and technological advances on leakages in the refined-oil pipeline system in the soil–groundwater environment. The article begins with a discussion of the various detection and monitoring techniques used to identify pipeline leakage and subsurface petroleum contamination. It then discusses contaminant migration and transformation pathways, notably vertical infiltration, groundwater plumes, hydrogeological controls and natural attenuation. It then reviews the practice of conducting environmental and health risk assessments using conceptual site models, contaminant toxicity and exposure pathways and uncertainty analysis. Conventional, biological, nature-based, emerging, and hybrid remediation technologies are then assessed in the review with a focus on their relevance to deep soil and groundwater contamination. Last, it suggests an integrated and adaptive management plan for the future response to oil pipeline leaks. This review aims to integrate knowledge gained from a field study of pipeline pollution events and the latest monitoring, modeling, risk analysis, and sustainable remediation technologies to establish a scientific framework for the safe operation of pipelines, the effective control of pipeline pollution, and the resilient protection of soil and groundwater resources [22–24].

2. Detection and Monitoring of Refined-Oil Pipeline Leakage and Subsurface Pollution

2.1. General Principles of Leakage Detection and Environmental Monitoring

The key to refined-oil pipeline pollution management is detection and monitoring. A subsurface process is often what buried pipeline leakage entails, as opposed to the surface oil spill where oil films, odors, or ecological damage can be quickly noticed. Often, petroleum products will first pool near the pipeline trench; they can subsequently travel vertically through the vadose zone and into groundwater systems. Monitoring strategies should not only assess pipeline leakage but also the potential for contamination of soil, groundwater, vapor pathways, and receptors.

A leakage event from a refined oil pipeline should be investigated using a source-pathway-receptor (SPL) logic. The damaged pipeline section is the source, as is the illegal tapping point, corroded joint, valve chamber, or location of an operational failure. Soil pores, fractures, loess layers, preferential flow zones, groundwater flow fields, and vapor migration channels are all included in pathways. Receptors include agricultural soils, irrigation wells, drinking water wells, residents, crops and ecological systems. The Luoyang–Zhumadian pipeline case illustrates the need for this integrated approach: the pipeline leak was related to illegal tapping, the resulting pollution was not simply a problem along the pipeline but extended beyond this and into the deep soil and groundwater, necessitating extensive environmental investigation [25].

2.2. Conventional Leakage Detection Methods

While new technologies play a significant role in pipeline leak detection, conventional methods are also valuable because they are the first to indicate that something is amiss with the pipeline or in the local environment. These are done through visual inspection, through patrolling, through pipeline pressure analysis, through flow-balance, through odor reporting, through surface oiltrace, and manual sampling. In rural/agricultural settings, local inhabitants may also be informal early-warning observers, particularly when the oil smell is noticed, a film of oil on wells, or the occurrence of abnormalities in crops is detected.

However, the conventional methods have definite drawbacks. A visual inspection is only effective if leakage is at the surface or where there is a visible secondary sign of leakage. Pressure monitoring will only detect large or sudden releases and may not detect slow, intermittent, or small leaks. Ground-based sampling is generally reactive, not preventive, and is able to give reliable chemical information, but by the time the samples are taken, contaminants may have spread away from the source. In the Shanhua Town case, it was observed that the oil contamination was visible in wells after the oil had already leaked through the subsurface. This shows that after the initial leak, it takes time for the contamination to become visible in the environment [26,27].

Therefore, conventional detection should be considered as only one part of the pipeline protection work of the environment. It is most useful for initial screening, emergency verification and historical reconstruction, but is only valuable as part of a subsurface investigation and long-term monitoring of the site to ensure that risk management is based on accurate data.

2.3. Soil and Groundwater Sampling for Contamination Delineation

Soil and groundwater sampling are still the best means of establishing refined-oil contamination. Shallow agricultural soil as well as deeper materials in the vadose zone should be considered for sampling since the severity of the contamination in the subsurface could differ from the surface soil. In the case of pipelines that are buried, contamination may migrate through the near surface and become trapped at depth, especially at locations where the pipeline has leaked below the root zone or where permeable strata allow the migration to deeper levels. Thus, pipeline depth, soil stratigraphy, pipeline leakage history, groundwater depth, and possibly contaminant pathways should be taken into account in the sampling design.

The need for groundwater monitoring is even more important when the refined-oil components that are used in the product contain compounds that are soluble and mobile in groundwater (e.g., BTEX and MTBE). Monitoring wells should be located both close to the possible source and downgradient of the area in the direction of regional groundwater flow. Upgradient wells are also needed to differentiate background water quality from pipeline contamination. It has been found that the Luoyang–Zhumadian investigation involved 109 soil sampling points and 23 groundwater monitoring points, with a high sampling density that was necessary to define a complex leakage plume.

One of the biggest issues with sampling-based monitoring is the uncertainty of location. Petroleum contamination is frequently heterogeneous because refined oil can be a free phase, a residual phase, a dissolved phase, or a vapor phase. Some high concentration areas may not be encountered by a small number of boreholes, and drilling too many boreholes may lead to higher investigation costs and/or disturbance of contaminated strata. Sampling should thus be adaptive; initial results should inform the location of additional boreholes, the installation of monitoring wells, and lab analysis. This gradual approach enhances the accuracy of scientific research and the value of the money [2,28,29].

2.4. Hydrogeological Investigation as a Monitoring Prerequisite

The hydrogeological investigation is not only a supporting job but an integral part of the interpretation of detection and monitoring results. Concentrations of contaminants can be misleading if information on groundwater depth, hydraulic gradient, aquifer structure, permeability, recharge conditions, and preferential pathways is not understood. A high concentration at one location may be a local (residual) source, and a low concentration further from the source may be a migrating dissolved plume. Likewise, if shallow soil is not contaminated, then the deeper soil may be contaminated.

The vadose zone serves as a migration pathway as well as a long-term contaminant reservoir in the case of a refined-oil pipeline leakage. Petroleum hydrocarbons can be stored in the pores of the soil, bound to organic matter, trapped in low permeability layers, or gradually released into infiltrating water. However, in fractured media or loess, preferential flow may slow down the flow and create deep contamination that can be hard to identify using shallow sampling. The Shanhua Town case demonstrated that local loess soils and fractures allowed pollutants to migrate downward and deep groundwater systems allowed pollutants to migrate horizontally, creating a large contamination plume.

Based on this evidence, hydrogeological monitoring should be considered at the initial phase of a pipeline pollution investigation. To assess the direction of contaminants, groundwater-level monitoring, borehole logging, aquifer testing, stratigraphic interpretation, and flow-direction analysis must be performed and a location for the installation of monitoring wells must be determined. In this context, hydrogeology is able to move from a reactive approach to search for contamination to a predictive approach for delineating the plume [30].

2.5. Remote Sensing and Geophysical Detection Technologies

The use of remote sensing and geophysical methods is useful for screening and subsurface characterization at a larger scale. Anomalies in the surface, vegetation stress, soil moisture changes, and possible leakage-related disturbances can be detected through satellite imagery, unmanned aerial vehicles, infrared imaging, hyperspectral sensing, and thermal monitoring. The techniques are particularly applicable to long-distance pipelines traversing farmland, the urban fringe, rivers and environmentally sensitive areas.

Geophysical tools like ground-penetrating radar, electrical resistivity tomography, electromagnetic methods, and hydrogeophysical monitoring can assist in determining abnormal areas relating to petroleum contamination or disturbed soil, pipeline trenches, and preferential migration pathways for subsurface contamination. The advantages are that they are not as destructive as a drill and they can cover a larger area. Their interpretation is indirect, however. The geophysical anomalies could be caused by lithological changes, water content, salinity, buried objects, or by the interference of infrastructure, not by the presence of petroleum. Geophysical data should not be used to replace chemical sampling, rather it should be used to help select sampling locations and to enhance the conceptual site model [31].

Integration is the key to the future potential of remote sensing and geophysical technologies. Together with borehole data, groundwater monitoring, contaminant analysis and hydrogeological models, these technologies can help to minimize the uncertainty in plume mapping and help to better identify any hidden leakage early.

2.6. Smart Sensing, Artificial Intelligence, and Real-Time Monitoring

Smart monitoring technologies are becoming increasingly vital to the environmental management of pipelines in the next generation. Technologies such as distributed fiber-optic sensing, acoustic monitoring, Internet of Things sensor networks, wireless groundwater sensors, automated sampling systems, and real-time data platforms can deliver real-time data on pipeline integrity and environmental conditions. Artificial intelligence (AI) and machine-learning models can be used to further aid in the identification of abnormal pressure signals, leakage probability, sensor anomaly classification and plume migration forecast.

The key benefit of smart monitoring is from periodic inspection to dynamic risk management. Operators don't have to wait for pollution to be seen or for regular sampling events, but instead can detect abnormal signals earlier and target high-risk areas on pipelines. Digital twins can also incorporate pipeline operating information, soil properties, groundwater flow, contaminant transport, and remediation effectiveness in a single decision support platform.

However, the use of smart systems has practical constraints. Maintenance, calibration, data quality control and site-specific validation are all necessary when using a sensor network. Machine-learning models could be poor if the amount of training data is small, or if there is a significant difference in geology between training and testing locations. So, intelligent monitoring cannot be considered as an independent solution. Its success requires a team approach between digital technology, field investigation and regulatory control [32].

2.7. Critical Perspective on Integrated Monitoring Frameworks

Technology is not the problem in monitoring leakages in refined-oil pipelines; in fact, the technology is available, but its use is fragmented. Often, operation monitoring of pipelines, soil sampling, groundwater analysis, hydrogeological investigation, remote sensing, and risk assessment are carried out individually. This fragmentation can result in delays in source identification, underestimation of deep contamination, and a weakened remediation design. Detection and monitoring technologies for refined-oil pipeline leakage are shown in **Table 1**. An integrated monitoring framework should integrate early pipeline leakage detection, quick environmental screening, detailed soil and groundwater investigation, hydrogeological modeling, and long-term monitoring of the plume. This is especially relevant when shallow soil is considered relatively uncontaminated, but deep soil and groundwater are contaminated. Other critical tools that are also proposed to be important for intelligent management of spills are integrated monitoring platforms, artificial intelligence, autonomous systems, and digital twins [33].

Therefore, detection and monitoring should be understood as an adaptive process rather than a single investigation stage. Initial detection identifies possible leakage; detailed investigation defines contamination extent; long-term monitoring evaluates plume evolution; and intelligent systems support early warning and decision-making. For refined-oil pipeline leakage in soil–groundwater systems, this integrated approach is essential for reducing environmental risk, improving remediation efficiency, and protecting groundwater resources. An integrated monitoring architecture linking operational, surface, vadose-zone, groundwater, and digital data streams is shown in **Figure 1**.

Table 1. Detection and monitoring technologies for refined-oil pipeline leakage.

Monitoring Approach	Application Target	Strengths	Limitations	Best Use in Pipeline Leakage Management
Visual inspection and patrols	Surface oil traces, odor, vegetation stress, and evidence of illegal tapping	Low cost and easy to implement	Detects mainly visible or advanced leakage; poor for hidden subsurface releases	Initial screening and emergency confirmation
Pipeline pressure and flow monitoring	Pipeline integrity and leakage signals	Useful for rapid detection of large leaks	May miss slow, small, or intermittent leakage	Operational early warning
Soil sampling	Surface and deep vadose-zone contamination	Provides direct chemical evidence	Spatially limited; may miss heterogeneous contamination	Source-zone and vertical contamination delineation
Groundwater monitoring wells	Dissolved contaminant plumes	Essential for plume mapping and trend analysis	Requires correct well placement and long-term monitoring	Groundwater risk assessment and remediation performance tracking
Geophysical methods	Subsurface anomaly detection and pathway identification	Non-invasive and spatially extensive	Indirect interpretation; requires validation by sampling	Guiding borehole placement and conceptual site model development
Remote sensing and UAVs	Surface disturbance, vegetation stress, large-area surveillance	Efficient for long pipeline corridors	Limited sensitivity for deep contamination	Regional screening and high-risk section identification
Fiber-optic and IoT sensors	Real-time pipeline and environmental monitoring	Enables continuous detection and early warning	Requires installation, calibration, and maintenance	Intelligent monitoring and adaptive management
AI and digital twins	Prediction, anomaly recognition, decision support	Integrates multi-source data and improves forecasting	Data-dependent and requires site-specific validation	Predictive leakage prevention and plume management

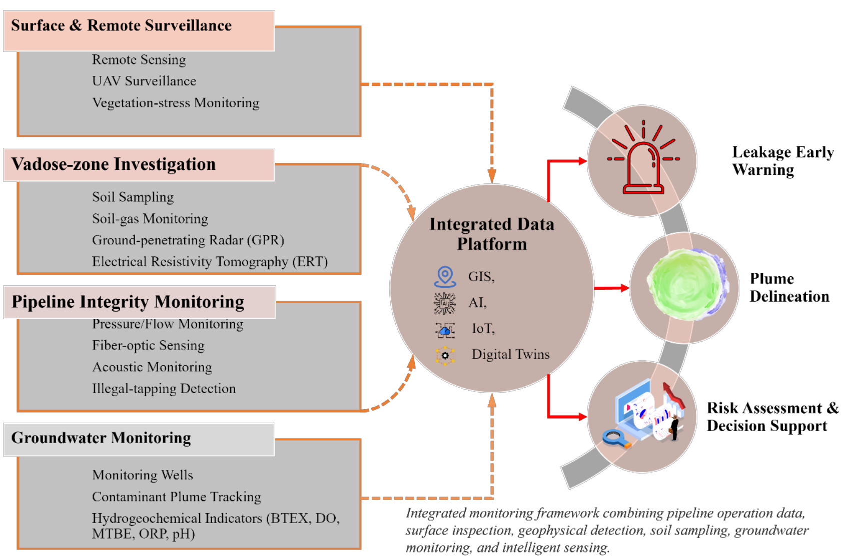

Figure 1. Integrated detection and monitoring system for refined-oil pipeline leakage.

3. Contaminant Migration and Transformation in Soil–Groundwater Systems

3.1. Characteristics of Refined-Oil Contaminants

Leaking of refined-oil pipelines releases a complex mixture into the subsurface environment. Refined products like gasoline and diesel oil have a high volatile, semi-volatile, soluble and biodegradable fraction of the oil, which reacts differently when released. Typical contaminants include benzene, toluene, ethylbenzene, xylene, naphthalene, methyl tert-butyl ether, volatile petroleum hydrocarbons and extractable petroleum hydrocarbons. The toxicity, water solubility, vapor pressure, sorption potential and biodegradation rate also vary among these compounds, and thus a refined-oil spill cannot be viewed as a single pollutant. It is more a dynamic mixture, one in which elements separate, move, change and weaken at varying rates rather than a fixed mixture.

The environmental risk associated with the leakage of refined oil is mostly due to the lighter, more mobile and toxic fractions. Of particular concern is benzene, which has a relatively high solubility and is highly toxic compared to the heavier petroleum hydrocarbons. MTBE is also of significance because it is highly soluble, moderately unimpressed by soil particles, tends not to undergo rapid natural degradation, and can travel long distances in groundwater. Larger diesel-range hydrocarbons (DCHs) and polycyclic aromatic hydrocarbon (PAH) molecules tend to be less mobile, but can remain as residual contamination in soil, thereby producing long-term secondary sources. The ability to move and stay in the pipeline, combined with the general persistence of the residual hydrocarbons, makes refined-oil pipeline leakage particularly hard to control. The attached case summary lists BTEX, naphthalene, MTBE, volatile organic compounds (VOCs) and extractable petroleum hydrocarbons (EPHCs) as key contaminants that must be assessed both for short- and long-term mobility and toxicity. **Table 2** presents the major groups of contaminants in the refined oil pipeline leak and their environmental significance [34–36].

Table 2. Major contaminants associated with refined-oil pipeline leakage and their environmental significance.

Contaminant Group	Representative Compounds	Main Environmental Behavior	Risk Concern	Monitoring Significance
BTEX	Benzene, toluene, ethylbenzene, xylene	Relatively soluble, volatile, and mobile in groundwater	Benzene has a high carcinogenic risk; BTEX may cause acute and chronic toxicity	Core indicators for refined-oil leakage and groundwater risk assessment
Oxygenated fuel additives	MTBE	Highly soluble, weakly sorbed, persistent in groundwater	Long-distance plume migration and drinking-water odor/taste concerns	Useful tracer for gasoline-related groundwater contamination
PAHs	Naphthalene and heavier aromatic hydrocarbons	Less soluble but persistent; tend to sorb to soil organic matter	Ecological toxicity and potential carcinogenicity	Important for evaluating long-term soil contamination
Volatile petroleum hydrocarbons	Light gasoline-range hydrocarbons	Partition into vapor, soil gas, and groundwater	Vapor intrusion, inhalation exposure, and explosion risk in confined spaces	Important for soil-gas and vadose-zone monitoring
Extractable petroleum hydrocarbons	Diesel-range and heavier petroleum fractions	Lower mobility but higher persistence in soil	Long-term residual source and ecological stress	Useful for evaluating residual petroleum mass
Free-phase petroleum	Light non-aqueous phase liquid (LNAPL) or residual oil phase	May accumulate above the water table or remain trapped in pores	A continuous secondary source of dissolved contamination	Critical for source-zone delineation and remediation design

3.2. Release Behavior and Source-Zone Formation

Migration starts with the formation of a source zone around the leakage site. Refined oil that escapes from a buried pipeline initially enters the surrounding backfill or native soil. Petroleum can be present as a free-phase liquid, residual-phase liquid, dissolved-phase contaminant in pore water, or vapor-phase components in soil gas depending on the amount of leakage, pressure, time of leakage, type of petroleum, soil texture, and moisture. These stages don't exist in isolation. Petroleum can flow downward by gravity; residual petroleum can be slowly dissolved into infiltrating water; volatile compounds can partition into soil gas; and soluble fractions can enter groundwater.

One of the challenges with pipeline leaks is the lack of knowledge about the history of the leak. Sometimes, illegal tapping, corrosion, or small pipeline defects can persist for weeks or months or even years undetected. The initial source zone may have created a complicated secondary contamination pattern before the surface signs and symptoms of contamination were observed. With respect to the Luoyang-Zhumadian pipeline incident, the pipeline leakage site was determined to be a result of illegal tapping found in 2009, and the environmental investigation revealed that contamination had spread away from the pipeline and into the ground. This shows that source control is not sufficient to remove subsurface risk if there is residual petroleum in deep soil layers.

The sources are also not even. Petroleum does not migrate evenly through soil; it tends to migrate preferentially through connected pores, fractures, coarser layers and disturbed materials of the trenches. This results in non-uniform contamination boundaries and concentration hot spots. The extent of contamination may be underestimated by a monitoring borehole that is just a few metres away from a preferential pathway. Hence, the source-zone characterization needs to be an integration of chemical sampling, geological logging, hydrogeological interpretation, and, if available, geophysical evidence [37].

3.3. Vertical Migration through the Vadose Zone

Vertical migration in the vadose zone is one of the most significant but often overlooked factors in the leakage of refined-oil pipelines. The vadose zone is not simply a passive zone under the ground surface and above the groundwater. It performs four functions: as a conduit, as a reservoir for contamination, as a reaction site, and as a delayed-release reservoir. Petroleum components can flow downwards due to gravity, capillary forces, infiltration recharge and/or pressure differences created by leakage. As part of this process, part of the petroleum mass remains in soil pores, part volatilizes, part dissolves into pore water, and part is biodegraded.

Contamination behavior is closely related to the depth and structure of the vadose zone. Petroleum can be rapidly introduced to groundwater in areas of shallow groundwater, causing rapid groundwater contamination. If the vadose zone is deep, the downward movement may be slower, but the contaminants may stay in the deep soil for a longer time. The Shanhua Town case is especially interesting because the shallow (agricultural) soils were generally within reasonable limits, while the deeper soils in the vicinity of the leakage were severely contaminated. The contamination in the soil was found to have a downward "umbrella-shaped" distribution around the contamination area, implying that surface soil quality can be misleading as an indicator of environmental safety.

The pattern is of significance for investigation and remediation. Avoid restricting assessment to top soil as deep residual contamination may not be detected. Remediation may only involve the removal of topsoil, and the remainder of the soil, the vadose zone, may continue to leach contaminants into groundwater. So, for the refined-oil pipeline sites, vertical profiling is necessary. To assess the presence of residual petroleum that could continue to serve as a long-term source, deep borehole drilling, multi-depth sampling, soil gas monitoring, and vadose-zone modeling will be required [38].

3.4. Groundwater Plume Development and Migration

After petroleum contaminants get to groundwater, they change from a primarily vertical movement to a mostly horizontal movement, or plume migration. Dissolved contaminants flow on groundwater flow paths where they transform as a result of advection, dispersion, diffusion, sorption, biodegradation, and dilution. The plume does not have to be elliptical. The geometry is influenced by aquifer heterogeneity, the hydraulic gradient, recharge, pumping activities, preferential pathways and the persistence of the source zone.

Groundwater contamination can be more significant than soil contamination, where it can migrate away from the impacted area to impact wells, irrigation systems and drinking water resources. For the Luoyang-Zhumadian case, the extent of groundwater contamination was more severe than the surface soil contamination, and the contaminant plume extended in the direction of regional groundwater flow to the east. The reported plume was about 700 m long (north–south) and 1,500 m wide (east–west), totaling about 0.77 km^2. This spatial resolution represents a local pipeline leak that becomes a regional problem related to groundwater management.

Groundwater quality in the groundwater plume also varies with time. Less soluble compounds can be transferred ahead of heavier hydrocarbons and biodegradable compounds can decrease near the source if electron acceptors are present. On the other hand, those compounds that are persistent or weakly sorbed can be detected long downstream. In time, a decrease in concentration should therefore be taken with a pinch of salt. A declining trend can be caused by natural attenuation or the effectiveness of the remediation, but it can also be caused by plume movement away from the monitoring wells, dilution, or a lack of monitoring in the lower portions of the plume. The case summary indicates that pollutant concentrations have overall decreased with time because of natural attenuation and past remediation efforts, but some contamination remains in a number of groundwater wells. This indicated that there was a risk of groundwater contamination but it was not completely removed [39].

3.5. Hydrogeological Controls on Migration and Persistence

Petroleum contaminant migration is governed by the hydrogeologic regional framework. The movement and accumulation of contaminants are dependent on soil texture, permeability, porosity, stratification, fracture development, groundwater depth, aquifer thickness, hydraulic conductivity and groundwater flow direction. Contaminant migration may be somewhat predictable in homogeneous porous media. However, in a heterogeneous geological environment, preferential flow paths can generate fast flow in the downward or lateral direction, which might be hard to detect and model.

Special attention should be given to loess areas, fractured strata and disturbed pipeline trenches. Loess may possess macropores, fissures and variable permeability zones that favor preferential infiltration. Pipeline construction can also disturb (i.e., trenching) natural soil properties by changing the composition of backfill material compared to that of the soil. These disorganized areas can serve as man-made flyways. The geology of the area allowed for long-distance groundwater contaminant transport, with local geology allowing for the downward migration of loess and the horizontal migration of deep groundwater systems; the report concluded this.

Hydrogeological controls also affect the possibility of remediation. Monitored natural attenuation (MNA) or targeted bioremediation of a shallow, slow-moving plume in a uniform aquifer may be appropriate. Long-term monitoring, hydraulic control and combined treatment technologies may be necessary for a deep plume in a heterogeneous aquifer. Thus, the hydrogeological characterization should not be used as background information but directly inform the risk assessment, monitoring network design, technologies selected, and end points for remedial action [40,41].

3.6. Transformation and Attenuation Processes

A series of transformation and attenuation reactions occur in soil–groundwater systems as petroleum contaminants travel through the soil. Vapor intrusion can increase concentrations of some light hydrocarbons, but it can also decrease concentrations of some light hydrocarbons due to volatilization. Hydrophobic compounds can become immobile due to sorption, but can also persist in the environment for long periods of time if they are slowly desorbed. Dissolution processes move contaminants into groundwater, making them more mobile in the groundwater. Biodegradation removes contaminant mass, particularly for BTEX and some petroleum hydrocarbons, and is dependent upon microbial communities, temperature, nutrients, oxygen, nitrate, sulfate, iron, methane production and other redox conditions.

Natural attenuation is therefore both useful and unpredictable. It can lower concentrations of contaminants without extensive engineering efforts, though it is not a given if concentrations lower. Four conditions for natural attenuation to be scientifically defensible are (1) evidence of stable or declining plumes; (2) decreasing contaminant mass; (3) suitable geochemical conditions; and (4) protection of receptors from degradation by-products. Biodegradation of petroleum materials can produce a redox zonation in an aquifer, in which oxygen is depleted close to the petroleum source, and anaerobic processes dominate further downgradient. This zonation has implications for degradation rates and should be considered in monitoring programmes [42,43].

One of the drawbacks is that the different components of the refined oil will attenuate at various rates. BTEX compounds can break down in ideal conditions, while MTBE can break down and travel further. Higher molecular weight hydrocarbons can be retained in soil and continue to emit dissolved phase hydrocarbons. As a result, a decrease in the concentration of one pollutant group doesn't necessarily indicate that the entire pollution system is recovering. Not just total petroleum hydrocarbon trends should be used when assessing risk; other compounds, particularly those that are slowest to attenuate and most mobile, should be taken into account.

3.7. Climatic and Land-Use Influences on Contaminant Behavior

Land use and climate are additional factors that add to the complexity of contaminant migration. Residual petroleum in the vadose zone can be mobilized and downward leaching can be increased due to rainfall infiltration. Seasonal changes in groundwater levels may cause petroleum residues to spread out across the capillary fringe, thereby expanding petroleum-contaminated areas. Drought conditions can affect dilution and biodegradation, and heavy rains can affect the recharge and displacement of the plumes. Irrigation in agricultural areas can change groundwater flow patterns, leaching, and provide new exposure opportunities related to crop cultivation and water use.

The proposed article structure is appropriate and highlights the new challenges of climatic variability and complex hydrogeological conditions in oil spill management. This is becoming a significant problem, as after initial leakage, groundwater alteration due to changes in recharge or extraction may change the behavior of the plumes. The traditional site assessment, which has been static, may therefore underestimate future risk. A more resilient approach would consider scenarios related to seasonal and climate change, especially in those locations where groundwater is utilized for irrigation and/or potable applications [44].

3.8. Critical Synthesis and Research Needs

Refined-oil contamination in a soil–groundwater system should be considered a coupled (more than one phase), time-dependent process. Many site investigations have a problem by breaking the issues of soil pollution, groundwater pollution and pipeline failure analysis into distinct parts. In fact, these components will be dynamically connected. The source zone is formed by a leak in a buried pipeline; the source zone supplies the vadose zone; the release of contamination from the vadose zone to groundwater provides a source path for groundwater transport; and residual contamination may persist and continue to pose a risk after the spill is visible.

The case evidence indicates that shallow soils may be relatively protected, while deep soil and groundwater are very much impacted. The discovery contradicts the basic methods of surface-based evaluation and justifies deep vertical profiling, hydrogeological modelling and long-term monitoring. Future research should aim to quantify residual source strength, enhance prediction of preferential flow in heterogeneous media, identify the differences between real attenuation and plume displacement, and incorporate contaminant transport models with real-time monitoring data. This is a critical improvement that enables moving from a reactive to a predictive, adaptive and risk-based approach to leakage management on refined-oil pipelines [45].

4. Environmental and Health Risk Assessment

4.1. Conceptual Framework for Risk Assessment

Environmental and health risk assessment is an integral part of refined-oil pipeline leakage management, as it transforms contamination information into decision-relevant information. However, risk assessment is not as simple as comparing pollutant concentrations to regulations in soil–groundwater systems. A scientifically sound evaluation should include an explanation of how the contaminant was released, how it traveled, where it ended up, which receptors may be exposed, and whether the contaminant risk is growing, leveling off, or decreasing. Thus, the conceptual site model should be considered as the basis for the assessment.

The conceptual site model should involve elements of the leakage source, soil and vadose-zone pathways, groundwater transport pathways, exposure routes and sensitive receptors for refined-oil pipeline leakage. This is especially significant in situations where contamination is located above or below the surface and in close proximity to human activities. In the Luoyang–Zhumadian pipeline, the shallower layers of agricultural soils generally had contamination levels that were lower than national guidelines, while the deeper layers of soil in the areas where the pipeline leaked and groundwater in the zone were highly contaminated with petroleum. This shows that while there may appear to be no surface danger, there could be major subsurface danger [46].

One of the biggest flaws of many pipeline contamination studies is viewing soil and groundwater as two distinct environmental media. In fact, they are linked by leaching, capillary exchange, vapour transfer and fluctuation of groundwater. Even if the surface contamination seems to be limited, a deep contaminated soil zone can continue to release soluble pollutants to groundwater for years. Therefore, risk assessments should consider current contaminant levels, as well as long-term source strength and contaminant rebound. The key elements of the SPR components used to assess the risk of potential leaks from refined-oil pipelines are summarized in **Table 3**.

Table 3. Source-pathway receptor framework for environmental and health risk assessment.

Risk Component	Main Elements in Refined-Oil Pipeline Leakage	Critical Assessment Questions	Implications for Management
Source	Damaged pipeline, illegal tapping point, residual petroleum in deep soil, free-phase oil	Is the source removed? Does residual contamination remain? Is the source still releasing pollutants?	Determines whether source removal, containment, or long-term control is needed
Primary pathways	Vertical infiltration, preferential flow, loess fractures, pipeline trench backfill	How did pollutants migrate downward? Are there fast pathways to groundwater?	Guides deep soil sampling and vadose-zone monitoring
Secondary pathways	Groundwater flow, dissolved plume migration, vapor movement, irrigation water use	Is the plume expanding, stable, or shrinking? Can vapors reach buildings?	Determines monitoring well placement, vapor assessment, and water-use restrictions
Human receptors	Residents, farmers, well users, workers, children, sensitive populations	Are people exposed through drinking water, irrigation, soil contact, or inhalation?	Supports health risk assessment and community protection
Ecological receptors	Agricultural soil, crops, soil microorganisms, shallow groundwater ecosystems	Is soil function or crop production affected?	Supports ecological restoration and agricultural land management
Risk modifiers	Hydrogeology, seasonality, groundwater extraction, rainfall, land use	Could future conditions change exposure or plume behavior?	Requires adaptive and scenario-based risk assessment

4.2. Soil Pollution Risk Assessment

There is a need to differentiate surface soil, root-zone soil, deep vadose-zone soil, and source-zone soil in soil risk assessment at sites where refined oil leakage has occurred. The assessment of surface soil is of significance in agricultural production, dermal contact, dust inhalation, and ecological exposure. For buried pipeline leakage, however, the most polluted soil may be found at depth, particularly close to the trench of the pipeline or close to the point of leakage. Limited assessment of shallow soil can lead to an underestimation of the contaminant mass in the soil and future groundwater risk.

The effects of petroleum hydrocarbons in soil depend on their physical and chemical properties. Volatile chemicals, like benzene and toluene, can be a source of vapor intrusion and inhalation exposure. Lighter petroleum fractions may volatilize, while others that are semi-volatile and heavier can remain in the soil and impact soil structure, microbial activity, and plant growth. Hydrophobic compounds can be sorbed onto soil particles for a very long time and more soluble components can move downward with infiltration. The assessment of soil risk should not only be based on total petroleum hydrocarbons (TPH) concentrations but also include concentrations of specific toxic and mobile contaminants, such as BTEX, PAHs, MTBE, volatile petroleum hydrocarbons (VPHC), and extractable petroleum hydrocarbons (EPHC).

The significance of the case summarized in this attached report is that it demonstrates that the contamination of the soil had an "umbrella-shaped" vertical distribution around the leakage point. This pattern indicates that downward infiltration and lateral spreading of contamination in the vadose zone were the controlling factors, not just surface deposition. Three-dimensional delineation is needed from a risk perspective on such a pattern. The contamination map would not be sufficient, as the main risk might be at a depth of tens of metres [47].

4.3. Groundwater Pollution Risk Assessment

The primary risk following the leakage of a refined oil pipeline is often groundwater risk. When a contaminant is released into an aquifer, it can spread beyond the line of the pipeline and adversely impact wells, irrigation systems and drinking-water supplies. Groundwater plumes can spread along hydraulic gradients and cause regional environmental management issues, unlike contaminated soil, which is often geographically contained around the source of the contamination.

The groundwater contamination in the Luoyang–Zhumadian area created a plume that stretched eastward and was estimated to cover an area of 0.77 km^2. This discovery highlights the need to perform a hydrogeological interpretation along with the chemical analysis in groundwater risk assessment. Concentrations alone do not indicate whether a plume is growing, staying the same size, or decreasing. The monitoring wells should be placed upgradient, in the source zone, across the plume and beyond the known contamination boundary. This design can minimize risk, particularly if the plume is narrow, deep, and/or is controlled by preferential flow, as without this design, the risk may be underestimated.

Water assessment should be done on exceedance and plume behavior. Exceedance analysis involves determining whether concentrations exceed drinking-water, irrigation water or groundwater quality criteria. Plume behavior analysis involves analyzing migration direction, trends in plume attenuation, contaminant mass, and future receptor impacts. The distinction is significant because a column of decreasing concentration might still be dangerous if it was moving toward wells. On the other hand, if hydraulic containment or natural attenuation is effective, a well with a high concentration in the source zone may be a localized contamination source and not a wide-spread contamination hazard. Hence, groundwater risk should be viewed as a dynamic and not as a compliance outcome [48].

4.4. Human Health Risk Assessment

Both carcinogenic and non-carcinogenic risks of refined-oil contaminants should be considered in human health risk assessment. Benzene is typically the most important indicator of carcinogenic compounds, and the other compounds listed (toluene, ethylbenzene, xylene, naphthalene, MTBE, and petroleum hydrocarbon fractions) are potential for non-carcinogenic effects. Groundwater ingestion, dermal exposure when using water, inhalation of volatiles, vapor intrusion in buildings, soil exposure in agriculture, and indirect exposure due to irrigation and food production are considered exposure pathways in a rural and agricultural environment.

A serious difficulty is the fact that the exposure route can vary with time. Local concern may become the primary focus after oil leakage if local soils are directly contaminated or there is visible oil present. Ingestion of groundwater or irrigation exposure may be more critical as contaminants travel down. Vapor intrusion can be a concern in the long term if volatile hydrocarbons are present under buildings or where they are moving along preferential pathways. Hence, a health risk assessment needs to be path- and time-sensitive.

The impacted area in the attached report involved agricultural areas and groundwater resources for irrigation and local communities. When there is no setting, the identification of receptors becomes more significant. Household water supplies (from private wells) may pose other risks to residents than those associated with municipal water supplies. Occupational soil and water contact is possible for farmers. Children, elderly and people with chronic health conditions may be at greater risk of being exposed. Average assumptions of exposure should be avoided, and sensitive subpopulations and realistic local water-use behavior should be taken into consideration in a critical assessment [9,49,50].

4.5. Ecological and Agricultural Risk Assessment

Ecological and agricultural risks may be less considered than human health risks, but are quite applicable for pipeline leakage in rural areas. Petroleum contamination may impact the physical, chemical, biological and agronomic characteristics of soil, including aeration, water-holding capacity, nutrient cycling, microbial community structure, and plant root development. Soil ecological function can still be affected by soil contaminants even though levels are not detected at concentrations that are known to cause adverse health effects in humans. This is especially crucial for agricultural land where productivity of soils and safety of crops are of major concern.

Irrigation water quality could also be impacted if groundwater is contaminated. Petroleum constituents can be added to the root zone by contaminated groundwater used for irrigation, which can have an impact on crop health, soil microorganisms and food safety. The risk is related to the concentration of contaminants, the frequency of irrigation, the type of crops, soil characteristics, degradation in the soil and volatilisation. Many of the petroleum hydrocarbons could not be expected to be sufficiently bioaccumulated in edible tissues of plants, but some aromatic compounds and degradation products may be of concern in the food chain or ecologically. Thus, chemical safety and functional soil health are necessary to consider in agricultural risk assessment [51,52].

One of the major constraints encountered in most petroleum site evaluations is the reduction of ecological risk to regulatory exceedance. But agricultural systems need to be considered on wider parameters like microbial activity, enzyme function, phytotoxicity, crop yield and restoration potential. These are indicators that can be used to help answer the question of whether remediation has restored ecological function or simply lowered the concentration of contaminants to a numeric value.

4.6. Risk Modeling and Uncertainty Analysis

Assessment of the risk associated with leakage of refined-oil pipelines is always a question of uncertainty. The extent of leakage, the quantity of water released, its distribution underground, preferential pathways, rates of degradation, and future groundwater use are often not fully understood. Such uncertainties may have a significant impact on risk findings. For instance, if the leak duration is estimated too short, then the remaining mass of contaminant in the deep soil may also be estimated too short. A monitoring network designed with one water level survey may not be adequate to monitor plume movement in groundwater systems that have seasonal changes in groundwater flow direction. When natural attenuation is assumed but supported by inadequate geochemical data, there is the potential for underestimating long-term risk.

Uncertainty can be mitigated but not eliminated by modeling tools. GIS-based mapping can be used to draw maps of contamination patterns and receptor locations. Plume migration and future exposure can be estimated using groundwater flow and solute transport models. Variability in exposure parameters and hydrogeological conditions can be accounted for in a probabilistic risk assessment. If the data is large, machine-learning techniques can help to identify high-risk areas. The proposed soil contamination issues review framework properly brings GIS-based spatial risk mapping, numerical groundwater transport modeling, predictive analytics, uncertainty analysis and scenario simulation to the forefront as key tools of modern risk assessment [53–55].

But, if poorly constrained, models can give false confidence. A numerical model using sparse borehole information, high uncertainty in hydraulic parameters, or a short monitoring period may yield visually appealing predictions of the plume but may be unreliable. Thus, the results from these models should be interpreted as a support tool for decision-making and not as a representation of reality. Calibration, sensitivity analysis and uncertainty ranges, as well as comparison with independent monitoring data, shall be part of the critical model evaluation.

4.7. Risk Communication and Management Implications

The aim of risk assessment should be to assist management decisions. The decisions can range from emergency water-use restrictions to additional monitoring, the selection of remediation technology; land-use controls, well replacement, public health protection, and long-term environmental governance. The ability to communicate is particularly critical in leak situations, as it may cause uncertainty, distrust or concern among communities affected by the leak regarding the safety of their drinking water and agricultural land.

Risk communication should be clear about what is known, what is unknown, and steps being taken to protect others. Excluding excessive safety when it is based on shallow soil results can lead to a loss of public trust if groundwater is later found to be contaminated. On the other hand, if risk is exaggerated and pathways of exposure are not explained, there may be unnecessary fear. A balanced approach should communicate the distribution of contamination, the direction of plume movement, impacted receptors, monitoring outcomes, and planned remediation actions in a manner that is easily understood [56,57].

The biggest drawback to the traditional risk assessment method is that it is static. Most assessments are a static snapshot of contamination and only partially consider the evolution of risk. The leakage of refined-oil pipelines is a long-term dynamic process with source depletion, residual mass release, groundwater migration, natural attenuation, and potential plume rebound. Risk assessment should be cyclic, therefore. The conceptual site model should be updated for each new monitoring phase, along with a re-evaluation of exposure assumptions, plume behavior, and management.

4.8. Critical Synthesis

Environmental and health risk assessment for oil pipeline refinings, when considering oil pipeline leakage, must go beyond concentration comparisons. It should include aspects of contaminant toxicity, three-dimensional distribution of soil, groundwater plumes, hydrogeological controls, receptor vulnerability, ecological function and uncertainty analysis. The attached report illustrates that contamination of the deep soil and groundwater can persist despite the apparent lack of these impacts in the shallow soil, indicating a need for hydrogeologically-informed assessment of contamination to the subsurface.

Risk assessment approaches must be adaptive, probabilistic and receptor-based in the future. They should be able to locate the contaminants that are already present, as well as potential areas of migration, the likely timeframe of site contamination, and potential receptors under various conditions. The need for the highest level of research and practice with soil contamination issues is to build a decision-making system that combines monitoring, modeling, risk assessment, and remediation. This would enable pipeline leakage management to move from a reactive process to a proactive process of risk mitigation, protecting soil and groundwater resources over the long term [58–60].

5. Sustainable Remediation and Adaptive Management Strategies

5.1. Remediation Challenges in Refined-Oil Pipeline Leakage Sites

Technical challenges exist in remediating oil from refined-oil pipelines because contamination is often found in multiple environmental media and at varying depths. Buried pipeline leakage may result in residual petroleum zones in deep soil and dissolved contaminant plumes in groundwater that cannot be removed directly as in a surface spill. These zones are contiguous, but have varying responses to remediation. The trapped petroleum in the soil pores may result in source-zone contamination and the downgradient migration of groundwater may persist long after the original leakage has ceased. Remediation should not be thought of as a one-step process, but rather as a multi-step process that includes source control, plume management, exposure prevention, and long-term monitoring [61].

This complexity can be seen in the Luoyang–Zhumadian pipeline case. The report suggests that the soils in shallow agricultural areas were primarily within acceptable limits, while deeper soils near the leakage point and groundwater sites contained high levels of petroleum contamination. This groundwater contamination created a contamination source that turned into a larger groundwater problem (plume) of about 0.77 km^2. This pattern indicates that the more traditional surface-based remediation might not be adequate. Any successful strategy has to treat for the unknown residual contamination in the vadose zone and stop the ongoing discharge of contaminants into the groundwater [62–65].

5.2. Conventional Remediation Technologies and Their Limitations

Traditional remediation methods are still relevant in the case of refined-oil contamination, particularly where the levels of pollutants are high or when there is an immediate need to reduce risk. Excavation and off-site disposal can be quick methods for removing contaminated shallow soil, but they are not feasible for deep contamination as they can become technically challenging and costly. It may also not be feasible to excavate in a pipeline corridor where infrastructure safety, land use, or groundwater depth prevents the removal of large amounts of soil [66].

A system commonly used for contaminated groundwater is a pump and treat system. They can offer hydraulic control, lower the concentration of dissolved contaminants and limit the migration of the plume to sensitive receptors. But pump and treat can be labor-intensive and time-consuming. It is not as effective if contaminants are constantly being emitted from remaining source zones, low permeability layers or trapped petroleum phases. When this occurs, the groundwater concentrations can rise again following cessation of pumping. Thus, pump-and-treat is best suited to use as a containment or risk-control measure for a complex petroleum plume, rather than as a stand-alone remediation strategy [61].

Soil vapor extraction (SVE) and air sparging have been effective for volatile petroleum hydrocarbons (VPHCs) and BTEX compounds. Soil vapor extraction is used to extract volatile contaminants from the vadose zone and air sparging is used to introduce air into groundwater to increase volatilization and aerobic biodegradation. They are effective in permeable soil, but are not effective in heterogeneous or low-permeability soils. They may also not be as effective for heavier hydrocarbons with a high-octane rating, such as diesel, and less volatile hydrocarbons. Chemical oxidation and thermal treatment can provide rapid destruction of contaminants, but can be challenging to control due to potential alteration of the groundwater chemistry, degradation of soil structure, production of unwanted by-products, or significant energy consumption. Therefore, traditional technologies are very effective but cannot be considered as a complete solution [67].

5.3. Bioremediation and Monitored Natural Attenuation

A special aspect of bioremediation is its significance for leakage from a refined oil pipeline, because many of the hydrocarbons in petroleum oil are biodegradable under the appropriate conditions. Microbial degradation, dilution, sorption, volatilization, and chemical transformation can remove contaminant mass as a result of natural attenuation, bioaugmentation, and biostimulation. Monitored natural attenuation is attractive among these when the concentrations of the pollutants are decreasing, plumes are stable or decreasing, and receptors are protected. Can minimize remediation costs and ecological disturbance over aggressive engineering practices.

Natural attenuation should not, however, be a passive excuse to do nothing. They must be backed by substantial data, such as trends in concentration over time, stability of the plume, geochemical characteristics, biodegradation products, and protection of the receptor. The attached report indicates that concentrations of contaminants in the groundwater generally decreased with time as a result of natural attenuation and past remediation activities, with contamination still being present in some groundwater wells. This discovery demonstrates the benefits and constraints of using natural attenuation. It can help to lower contamination levels over time, but can not completely remove the risk to acceptable levels in a reasonable period of time if there is residual petroleum contributing to the contamination.

Biostimulation can be achieved by the addition of oxygen, nutrients, nitrate, sulfate or other electron acceptors to enhance biodegradation. Bioaugmentation involves adding special microbial strains or consortia to increase degradation capabilities. The methods may work for BTEX and some petroleum hydrocarbons, but they work best under specific site conditions, including pH, redox (electron-donating/accepting) state, nutrients, permeability, and contaminant concentration. In deep or heterogeneous aquifers, it is frequently the technical limitation that determines the amendment delivery. Biodegradation might be area limited if amendments are unable to reach contaminated areas uniformly. Thus, degradation potential alone must not be the only basis for designing bioremediation; hydrogeological transport capacity must also be considered [68].

5.4. Nature-Based and Low-Carbon Remediation Approaches

Due to the fact that petroleum contaminated sites may need to be managed for the long term, rather than cleaned up in one fell swoop, nature-based approaches are an increasingly important part of the equation. Constructed wetlands, rhizoremediation, biochar amendment, phytoremediation, and ecological restoration may contribute to the degradation, immobilization, water purification, and recovery of soil. In general, the techniques are less energy consuming and do not have the same impact as many traditional engineering techniques in an agricultural or rural setting.

Phytoremediation can help to condition shallow soil by increasing microbial activity in the rhizosphere, stabilising soil, and encouraging the degradation of hydrocarbons. It is not as well suited for deep vadose-zone contamination or deep groundwater plumes, however, since it may not reach main contaminated layers via plant roots. Petroleum-impacted water can be treated, and biodegradation, sorption, sedimentation and plant–microbe interaction can occur in constructed wetlands, but they need to have access to land and a proper hydraulic design. Biochar and organic amendments can enhance soil structure, bind hydrophobic compounds, and increase microbial activity, but can also lower the bioavailability of contaminants without necessarily lowering the mass of contaminants [69].

The key is that nature-based solutions (NbS) are not a blanket solution for engineering remediation. They are most appropriate for use in situations of low to moderate contamination, ecological restoration, polishing treatment, or long-term risk reduction. Hydraulic control, source removal, or enhanced bioremediation may be needed in conjunction with nature-based methods for high-concentration source zones or when the water table plume is moving quickly. They are important tools for sustainability and ecosystem recovery; however, their ability to deal with the depth, rate, and level of treatment that is accurate needs to be understood.

5.5. Emerging and Hybrid Remediation Technologies

New technologies are emerging that provide new opportunities for remediation of petroleum contamination in complex soil/groundwater environments. Nanomaterial-assisted remediation (NAR) techniques can be used to improve adsorption, catalytic degradation, or contaminant immobilization. In low-permeability soils, electrokinetic remediation (EKR) can enhance the transport and amendment delivery of contaminants. Surfactant-enhanced recovery can assist in the mobilization of trapped petroleum hydrocarbons and enhance removal from the source zone. Dissolved-phase contamination and plume control can also be dealt with by applying advanced oxidation, permeable reactive barriers and in situ amendment delivery systems.

Although the technologies are emerging, they need to be evaluated carefully before being implemented at scale. The secondary ecological risks of nanomaterials can arise from their movement outside of the treatment zone or their impact on the microbial communities. If hydraulic control is poor, the mobility of contaminants can be enhanced by the use of surfactants. The changes in soil geochemistry and pH are possible in electrokinetic systems, which require energy input. Advanced oxidation is effective, but can be expensive, and can create transformation products. Hence, the efficiency of removal is not the only criterion for evaluating innovation; sustainability, secondary pollution, cost, scalability and compatibility with site hydrogeology are also important to consider [70].

It is more realistic to use a combination of technologies to achieve remediation than to depend on one. A good approach to creating a pipeline run leak might be to use excavation or in situ treatment of the highest concentration source zone, soil vapor extraction for volatile substances, enhanced bioremediation for residual hydrocarbons, monitored natural attenuation for stable downgradient plumes, and long-term groundwater monitoring. The outline covers comparative assessment of remediation pathways for efficiency, cost-effectiveness, carbon footprint, scalability and suitability of remediation for soil and groundwater contamination, which is well placed. **Table 4** summarizes the comparative assessment of remediation technologies used to clean up refined-oil-contaminated soil and groundwater. This comparative perspective is important as the "best" technology is not necessarily the latest technology, but the most effective under particular geological, chemical, economic, and social circumstances that meet the requirement of reducing risk [71–75].

Table 4. Comparative evaluation of remediation technologies for refined-oil-contaminated soil and groundwater.

Remediation Technology	Main Target Medium	Advantages	Limitations	Suitable Application Scenario
Excavation and off-site disposal	Shallow contaminated soil	Rapid removal of high-concentration soil	Costly and impractical for deep contamination	Localized shallow source zones
Pump-and-treat	Contaminated groundwater	Provides hydraulic control and plume containment	Slow, energy-intensive, and prone to rebound	Dissolved plumes threatening receptors
Soil vapor extraction	Vadose-zone volatile hydrocarbons	Effective for volatile petroleum compounds	Limited in low-permeability or wet soils	BTEX-rich vadose-zone contamination
Air sparging	Groundwater and capillary fringe	Enhances volatilization and aerobic biodegradation	May spread vapors if poorly controlled	Permeable aquifers with volatile contaminants
Chemical oxidation	Soil and groundwater source zones	Rapid contaminant destruction	High cost; possible secondary geochemical impacts	High-risk source zones needing rapid reduction
Monitored natural attenuation	Groundwater plume	Low disturbance and low cost	Requires strong evidence of plume stability and receptor protection	Stable or shrinking plumes with active biodegradation
Biostimulation and bioaugmentation	Soil and groundwater	Enhances microbial degradation	Amendment delivery may be difficult in heterogeneous media	Biodegradable petroleum contamination
Phytoremediation	Shallow soil and near-surface groundwater	Low-carbon and landscape-compatible	Slow and limited by root depth	Low-to-moderate shallow contamination
Constructed wetlands	Contaminated water or pumped groundwater	Combines biodegradation, sorption, and ecological treatment	Requires land and hydraulic control	Polishing treatment and rural site management
Surfactant-enhanced recovery	Residual petroleum source zones	Mobilizes trapped hydrocarbons	May increase contaminant mobility if uncontrolled	Source zones with recoverable petroleum mass
Electrokinetic remediation	Low-permeability soil	Improves contaminant or amendment transport	Energy demand and pH changes may occur	Fine-grained or low-permeability contaminated soils
Hybrid remediation systems	Coupled soil–groundwater contamination	Combines the strengths of multiple methods	More complex design and monitoring	Deep, heterogeneous, long-term pipeline leakage sites

5.6. Technology Selection Based on Source–Pathway–Receptor Control

The selection of remediation technologies should be based on the source–pathway–receptor model. Pursuit of source control should be a top priority if the source is active or the residual petroleum mass is high. Plume containment or hydraulic control may be required if groundwater is moving contaminants to receptors. Then immediate risk management measures may be necessary (alternative water supply, well closure, limiting land use, vapor mitigation), if receptors are already exposed. This hierarchy discourages focusing on reducing concentration rather than exposure in remediation.

Technology selection can be especially challenging for deep vadose-zone contamination. It may be impossible to excavate, and may be difficult to deliver amendments in situations of low permeability or complex stratigraphy. In these situations, a combination of source treatment and long-term groundwater protection may be necessary for remediation. The choice of active remediation or monitored natural attenuation for groundwater plumes should be determined by the stability of the plume, the distance to the receptors, the toxicity of the contaminants, the ability of the groundwater to remediate the contaminants, and a reasonable timeframe for remediation. Monitored natural attenuation may be appropriate for a stable plume away from receptors, whereas active intervention may be necessary for a mobile benzene or MTBE plume approaching drinking-water wells [76,77].

There are many remediation projects that have a deficiency because the technology that is chosen is for availability or cost and not appropriate for the conceptual understanding of the site. Even sophisticated technologies can be unsuccessful if there is no accurate delineation of source zones, preferential pathways, and plume dynamics. Thus, it is desirable to keep remediation design iterative: continuously update the conceptual model based on monitoring data, inform technology selection based on the conceptual model, and use remediation performance to inform future management decisions.

5.7. Adaptive Management and Long-Term Monitoring

The sites of refined-oil pipeline leaks change over time, so adaptive management is crucial. The concentration of contaminants can change, increase, shift, and/or change form. The flow direction of groundwater can change with the seasons. Petroleum that has not been completely removed from the soil can slowly dissolve in the groundwater. Remediation systems can be effective at first, but lose efficiency when the mass of contaminants that can be easily removed is reduced. Fixed remediation plans are not effective in the face of these dynamic processes [2].

The essence of an adaptive strategy is to establish baseline characterization, implement phased remediation, monitor performance, conduct periodic risk reassessments, and make flexible technology adjustments. For instance, if there are high concentrations at the source, active remediation may be employed at the outset to lower the concentrations, and then monitored natural attenuation can be applied once the plume has reached a more stable state. Other treatment or hydraulic control may be needed if monitoring indicates plume expansion or contaminant rebound. This adaptive decision-making is particularly relevant at pipeline leaks, where there is uncertainty regarding the duration of the leaks and the mass of the contaminants remaining.

The monitoring of the wells should not be restricted to compliance wells. It should consist of source-zone wells, downgradient plume wells, lateral boundary wells, sentinel wells near receptors, and selected groundwater or soil-gas monitoring points where vapor or residual contamination is significant. Target concentrations should not be the only contaminants monitored; groundwater levels, redox conditions, electron acceptors, degradation products and changes in hydrogeology should also be monitored. This wider dataset enables managers to separate remediation progress from dilution or plume displacement or temporary concentration decreases [78].

5.8. Toward Sustainable and Resilient Remediation Frameworks

Sustainable remediation involves addressing some of the following: environmental protection, technical feasibility, economics, social acceptance, and carbon impact. Traditional remediation has tended to focus on the removal of contaminants but not adequately on energy use, greenhouse gas emissions, ecosystem impacts, waste, and long-term land restoration [79]. Sustainability is particularly critical for leaky refined-oil pipelines due to the need for remediation over years and the large volume of subsurface that must be addressed.

Multiple criteria need to be used to assess the remediation options within a sustainable framework, such as: risk reduction, contaminant mass removal, energy demand, carbon footprint, secondary pollution, cost, land-use compatibility, stakeholder acceptance, and long-term resilience. The use of digital tools, including GIS platforms, contaminant transport models and decision support applications, can assist in comparing alternative solutions and adapting remediation plans as new monitoring data becomes available. The features of the proposed article focus on integrated, adaptive, and resilient approaches to spill management, involving real-time decision support, artificial intelligence, big data, policy governance and community engagement. Remediation is not a 'bolt-on'; it requires these elements to be part of the process of transitioning from 'one-off' technical intervention to long-term environmental governance [80].

In general, remediation of refined-oil pipeline leakage needs to be changed from a technology- to a risk- and system-based model. The objective should go beyond just lowering pollutant levels at specific sampling locations to controlling sources, disrupting pathways, safeguarding receptors, rehabilitating soil–groundwater relations, and minimizing future risk. This will involve incorporating traditional engineering, bioremediation, NbS, new technologies, adaptive monitoring, and community-driven management. This is a more scientifically defensible approach and more appropriate for high-complexity pipeline leakage sites where long-term environmental risk is dominated by deep-soil contamination and groundwater plume migration [2,81,82]. The proposed adaptive and sustainable remediation framework for refined-oil pipeline leakage management is presented in **Figure 2**.

Figure 2. Adaptive and sustainable remediation framework for refined-oil pipeline leakage.

6. Conclusions

Leakage from refined-oil pipelines is a complex, long-term environmental hazard because leakage is not always limited to the spill site. Upon entering the subsurface, gasoline, diesel fuel, or mixed refined-oil products might partition into residual, dissolved, vapor, and sorbed phases, resulting in multi-media contamination affecting soil, the vadose zone, groundwater, and potentially human and ecological receptors. This review demonstrates that a pipeline leak does not fit the surface spill rubric but should be recognized as a combined soil–groundwater contamination event influenced by contaminant chemistry, contamination history, vadose-zone structure, aquifer conditions, and groundwater flow.

One of the main findings is that shallow soil conditions may not be a good indicator of the extent of subsoil contamination. Petroleum hydrocarbons can travel vertically through permeable soils, loess layers, fractured soils, and disturbed pipeline trenches, and into groundwater at buried pipeline leakage sites. If a contaminant is found in the deep vadose zone, it can serve as a long-term secondary source, releasing soluble contaminants such as BTEX and MTBE into groundwater. Site investigations should be conducted not only by examining the surface but also by taking vertical soil samples to the site depth, monitoring groundwater, characterizing the hydrogeology, and delineating the groundwater plume.

The most serious risk, often, is groundwater pollution. After entering aquifers, petroleum contaminants can travel well beyond the pipeline footprint and pose risks to drinking water sources, irrigation wells, crops, and communities. Hydraulic gradients, aquifer heterogeneity, recharge, seasonal fluctuations, and microbial degradation capacity play significant roles in the development, persistence, and attenuation of groundwater plumes. Risk assessment should be dynamic and predictive, incorporating contaminant concentration data, hydrogeological modeling, source-pathway-receptor analysis, receptor vulnerability, and uncertainty assessment.

The findings of this review also indicate that no single remediation technology is suitable for every leakage site in a refined-oil pipeline. Traditional techniques like excavation, pump-and-treat, soil vapor extraction, air sparging, and chemical oxidation offer rapid risk reduction but can be expensive, energy-intensive, or ineffective when contamination is deep and/or heterogeneous. More sustainable alternatives include bioremediation, monitored natural attenuation, phytoremediation, constructed wetlands, biochar amendments, and other nature-based solutions, but they require further study and research to understand their effectiveness based on contaminant type, depth, hydrogeology, and risk of exposure. New technologies, such as nanomaterial-assisted remediation, electrokinetic treatment, surfactant-enhanced recovery, hybrid systems, and intelligent monitoring, offer new possibilities but must be assessed carefully for their scalability, secondary effects, and long-term performance.

Leakage from refined-oil pipelines should be managed in the future not reactively but in an integrated, adaptive, and preventive manner within environmental governance. This necessitates integrating early detection of leakage, smart monitoring, hydrogeological investigations, contaminant transport modeling, risk-based decision-making, sustainable remediation, and long-term performance monitoring. This transition can be aided by AI, digital twins, sensor networks powered by the Internet of Things, geophysical monitoring, and GIS-based risk mapping, but these need to be grounded in solid field data and a site-specific hydrogeological understanding.

A system-based framework integration of pipeline integrity, subsurface contaminant behavior, receptor protection, remediation sustainability, and community risk communication is needed overall to effectively protect soil and groundwater resources. This approach can enhance early warning, reduce uncertainty, help select technology, and make pipeline infrastructure more resilient to environmental management challenges.

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References

[1] Druetta, P., Frabotta, R., Cavallo, G.L., 2024. Transport by Pipelines and Its Optimization. Springer: Cham, Switzerland.

[2] Song, Q., Zhou, B., Song, Y., et al., 2025. Microbial community dynamics and bioremediation strategies for petroleum contamination in an in-service oil Depot, middle-lower Yellow River Basin. Frontiers in Microbiology. 16, 1544233.

[3] Zhihuan, F., 2025. Pipeline Transportation: Energy Arteries Spanning Thousands of Miles. In: Lu, H. (Ed.). A Brief History of Transportation in China. Springer: Singapore. pp. 461–483.

[4] Raney, J.M., 2024. Assessing the Efficacy of Hydraulic Pumping as a Remediation Method of a Subsurface Light Non-Aqueous Phase Liquid Spill in Arroyo Grande, California [Master's Thesis]. California Polytechnic State University: San Luis Obispo, CA, USA.

[5] Potter, T.L., 2019. Analysis of petroleum contaminated soil and water: An overview. In: Calabrese, E.J., Kostecki, P.T. (Eds.). Principles and Practices for Petroleum Contaminated Soils. Routledge: New York, NY, USA. pp. 1–14.

[6] Sharafi, S., Salehi, F., 2025. Comprehensive assessment of heavy metal (HMs) contamination and associated health risks in agricultural soils and groundwater proximal to industrial sites. Scientific Reports. 15(1), 7518.

[7] Otegui, J.L., Cirimello, P., Carfi, G., 2026. Third-party damage in a low-risk area: The case of an oil pipeline. Engineering Failure Analysis. 183, 110251.

[8] Apergis, N., Mustafa, G., Dastidar, S.G., 2021. An analysis of the impact of unconventional oil and gas activities on public health: New evidence across Oklahoma counties. Energy Economics. 97, 105223.

[9] Sibe, L., Orij, O., Wonodi, A., 2026. Health Risk Assessment of Children and Adults Exposed to Hydrocarbon Polluted Soils and Groundwater in K-Dere and Kpor Communities, Ogoni, Nigeria. Asian Journal of Research in Biosciences. 8(1), 71–94.

[10] Sae-Ju, J., Chotpantarat, S., Thitimakorn, T., 2020. Hydrochemical, geophysical and multivariate statistical investigation of the seawater intrusion in the coastal aquifer at Phetchaburi Province, Thailand. Journal of Asian Earth Sciences. 191, 104165.

[11] Du, M., Li, M., Liu, W., et al., 2025. Field and laboratory study on the distribution, fate and transport of polycyclic aromatic hydrocarbons in the loess porous medium at a refinery polluted site: Understanding the soil-groundwater interface. Organic Geochemistry. 200, 104902.

[12] Guo, W., Wang, X., Liu, S., et al., 2022. Long-term petroleum hydrocarbons pollution after a coastal oil spill. Journal of Marine Science and Engineering. 10(10), 1380.

[13] Wang, M., 2024. Migration rules of petroleum pollutants in water and soil: A review. Petroleum Science and Technology. 42(25), 4281–4296.

[14] Bala, B., Tar, U.A., 2020. The giant of Africa? Explaining the Nigerian governance, security, and development paradox. In: Omeje, K. (Ed.). The Governance, Security and Development Nexus: Africa Rising. Palgrave Macmillan: Cham, Switzerland. pp. 315–339.

[15] Sallal, A.K., 2026. Oil Spill Cleanup in the Marine Environment: How to Use Current Technology to Restore Oil Spills. Water Environment Research. 98(4), e70376.

[16] Zhang, Y., Sun, Y., Yan, Y., et al., 2026. Research Status, Challenges and Future Perspectives of Geological Hazard Monitoring Methods in Mining Areas. Remote Sensing. 18(9), 1333.

[17] Hassani, S., Dackermann, U., 2023. A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring. Sensors. 23(4), 2204.

[18] Mehla, S., Paul, A.R., Periasamy, S., et al., 2026. AM Supported Sensor Technologies in Critical Minerals Exploration, Sorting, and Gas Sensing. In: Bhargava, K., Brandt, S., Batterham, M., et al. (Eds.). Additive Manufacturing for Critical Minerals. Springer: Singapore. pp. 134–167.

[19] Koohmishi, M., Kaewunruen, S., Chang, L., et al., 2026. State-of-the-art technologies integrated with InSAR: A focus on structural health monitoring of railway infrastructure. Structural Control and Health Monitoring. 2026(1), 5526499.

[20] Ge, L., Zhang, C., Tian, G., et al., 2021. Current trends and perspectives of detection and location for buried non-metallic pipelines. Chinese Journal of Mechanical Engineering. 34(1), 97.

[21] Yan, M., Li, J., Huang, X., et al., 2025. Comprehensive Review of Research on Buried Gas Pipeline Leakage. Journal of Pipeline Systems Engineering and Practice. 16(4), 03125003.

[22] Li, B., Wu, P., Yang, Z., et al., 2025. Mechanism of landfill leakage induced by surface subsidence and cracking during deep mining and the migration law of pollutants in groundwater. International Journal of Geomechanics. 25(9), 04025196.

[23] Lu, S., Yang, F., Liu, L., et al., 2025. Design and feasibility of acid gas reinjection with corrosion mitigation: A case study from Tahe Oilfield, China. Results in Engineering. 25, 104576.

[24] Eissa, B., Watson, M., Arbad, N., et al., 2025. A Review of Key Challenges and Evaluation of Well Integrity in CO_2 Storage: Insights from Texas Potential CCS Fields. Sustainability. 17(13), 5911.

[25] Zheng, J., Wang, C., Liang, Y., et al., 2022. Deeppipe: A deep-learning method for anomaly detection of multi-product pipelines. Energy. 259, 125025.

[26] Chu, X., Chen, P., Xu, Y., et al., 2026. Application of Near-Infrared Spectroscopy in Pipeline Transportation of Refined Petroleum Products. In Near Infrared Spectroscopy in Petroleum Refinery and Chemical Industry. Springer: Singapore. pp. 481–493.

[27] Wu, Y., Gao, L., Chai, J., et al., 2024. Overview of health-monitoring technology for long-distance transportation pipeline and progress in DAS technology application. Sensors. 24(2), 413.

[28] Qiu, C., Xiao, H., Zheng, Y., et al., 2025. Research on VOCs Composition Emissions in the Oil Transport Link Based on Multi-source Detection Data. In Proceedings of the 2025 International Conference on Intelligent Transportation and Future Mobility (ITFM2025), Guilin, China, 11–13 April 2025.

[29] Devatha, C., Vishnu Vishal, A., Purna Chandra Rao, J., 2019. Investigation of physical and chemical characteristics on soil due to crude oil contamination and its remediation. Applied Water Science. 9(4), 89.

[30] Slater, L., Binley, A., 2021. Advancing hydrological process understanding from long-term resistivity monitoring systems. Wiley Interdisciplinary Reviews: Water. 8(3), e1513.

[31] Arkoprovo, B., Adarsa, J., Animesh, M., 2013. Application of remote sensing, GIS and MIF technique for elucidation of groundwater potential zones from

a part of Orissa coastal tract, Eastern India. Research Journal of Recent Sciences. 2(11), 42–49.

[32] Mahmoud, A.A., Hasan, R., 2025. A Comprehensive Survey on Pipeline Monitoring Technologies: Advancements, Challenges, Market Opportunities and Future Directions. Journal of Pipeline Science and Engineering. DOI: https://doi.org/10.1016/j.jpse.2025.100353

[33] Wu, T., Chen, Y., Deng, Z., et al., 2023. Oil pipeline leakage monitoring developments in China. Journal of Pipeline Science and Engineering. 3(4), 100129.

[34] Wei, Y., Chen, Y., Cao, X., et al., 2024. A critical review of groundwater table fluctuation: Formation, effects on multifields, and contaminant behaviors in a soil and aquifer system. Environmental Science & Technology. 58(5), 2185–2203.

[35] Zhao, Y., Song, J., Cheng, K., et al., 2024. Migration and remediation of typical contaminants in soil and groundwater: A state of art review. Land Degradation & Development. 35(8), 2700–2715.

[36] Zeng, J., Tabelin, C.B., Gao, W., et al., 2023. Heterogeneous distributions of heavy metals in the soil-groundwater system empowers the knowledge of the pollution migration at a smelting site. Chemical Engineering Journal. 454, 140307.

[37] Xia, J., Wang, J., Zhang, L., et al., 2022. Migration and transformation of soil mercury in a karst region of southwest China: Implications for groundwater contamination. Water Research. 226, 119271.

[38] Jiao, J., Befus, K.M., Zhang, Y., 2024. Soil contaminants pose delayed but pervasive threat to shallow groundwater. Journal of Hydrology. 634, 130994.

[39] Bonnière, A., Khaska, S., Le Gal La Salle, C., et al., 2024. Long-term impact of wastewater effluent discharge on groundwater: Identification of contaminant plume by geochemical, isotopic, and organic tracers' approach. Water Research. 257, 121637.

[40] Hamed, Y., Houda, B., Ahmed, M., et al., 2023. North Western Sahara aquifer system hydrothermal and petroleum reservoirs dynamics: A comprehensive overview. Arabian Journal of Geosciences. 16(4), 247.

[41] Attobrah, B.N., Gyasi, E.K., Amoateng, E.A., et al., 2026. Hydrogeological Controls on Groundwater Contamination from Petroleum Operations: Contaminant Migration, Aquifer Vulnerability, and Assessment Methods. Interdisciplinary Studies on Applied Science. 3(1), 66–75.

[42] Adeniran, M.A., Oladunjoye, M.A., Doro, K.O., 2023. Soil and groundwater contamination by crude oil spillage: A review and implications for remediation projects in Nigeria. Frontiers in Environmental Science. 11, 1137496.

[43] Sheng, Y., Jiang, W., Zhang, M., 2023. Mobilization, Speciation, and Transformation of Organic and Inorganic Contaminants in Soil–Groundwater Ecosystems. Applied Sciences. 13(20), 11454.

[44] Kaushal, S.S., Mayer, P.M., Vidon, P.G., et al., 2014. Land use and climate variability amplify carbon, nutrient, and contaminant pulses: A review with management implications. Journal of the American Water Resources Association. 50(3), 585–614.

[45] Grimm, N.B., Foster, D., Groffman, P., et al., 2008. The changing landscape: Ecosystem responses to urbanization and pollution across climatic and societal gradients. Frontiers in Ecology and the Environment. 6(5), 264–272.

[46] Oyebamiji, A.R., Hoque, M.A., Whitworth, M., 2025. Regional assessment of groundwater contamination risk from crude oil spillages in the Niger Delta: A novel application of the source-pathway-receptor model. Earth Systems and Environment. 9, 117–133.

[47] Brusseau, M.L, 2019. Soil and groundwater remediation. In: Brusseau, M.L., Pepper, I.L., Gerba, C.P. (Eds.). Environmental and Pollution Science. Elsevier: Amsterdam, The Netherlands.

[48] Mao, X., Zhang, S., Wang, S., et al., 2023. Evaluation of human health risks associated with groundwater contamination and groundwater pollution prediction in a landfill and surrounding area in Kaifeng City, China. Water. 15(4), 723.

[49] Ghobakhloo, S., Khoshakhlagh, A.H., Alwan, N., et al., 2024. Health risk assessment of exposure to BTEX and PAH compounds in workers of burnt oil recycling factory: Simulation using Monte Carlo method. Environmental Processes. 11(3), 37.

[50] Muthwa, B., 2020. An Overview of the Occurrence, Evaluation and Remediation of Petroleum Hydrocarbon Contamination in South Africa: Case Studies of Contamination from Filling Stations in Gauteng. University of the Witwatersrand: Johannesburg, South Africa.

[51] Shi, P., Xiao, J., Wang, Y., et al., 2014. Assessment of ecological and human health risks of heavy metal contamination in agriculture soils disturbed by pipeline construction. International Journal of Environmental Research and Public Health. 11(3), 2504–2520.

[52] Ugochukwu, U.C., Ochonogor, A., Jidere, C.M., et al., 2018. Exposure risks to polycyclic aromatic hydrocarbons by humans and livestock (cattle) due to hydrocarbon spill from petroleum products in Niger-delta wetland. Environment International. 115, 38–47.

[53] Chen, Y., 2024. Risk and Reliability Analysis for Oil

and Gas Pipelines Using Data-Driven Methods [PhD Thesis]. University of Alberta: Edmonton, AB, Canada.

[54] Zhang, B., Zhu, Z., Jing, L., et al., 2013. Pilot-Scale Demonstration of Biosurfactant-Enhanced In-Situ Bioremediation of a Contaminated Site in Newfoundland and Labrador. The Harris Centre: Folsom, CA, USA.

[55] Makanjuola, B.C., 2019. Assessment of Air, Water Quality and Health Impact on the Environment of Petrol Stations in Ado Local Government Area of Ekiti State, Nigeria [PhD Thesis]. Kwara State University: Ilorin, Nigeria.

[56] Haimes, Y.Y., 2008. Risk Modeling, Assessment, and Management. John Wiley & Sons: Hoboken, NJ, USA.

[57] Aven, T., 2013. On how to deal with deep uncertainties in a risk assessment and management context. Risk Analysis. 33(12), 2082–2091.

[58] National Academies of Sciences, Engineering, and Medicine, 2016. Spills of Diluted Bitumen from Pipelines: A Comparative Study of Environmental Fate, Effects, and Response. National Academies Press: Washington, DC, USA.

[59] Ragothaman, A., Anderson, W.A., 2017. Air quality impacts of petroleum refining and petrochemical industries. Environments. 4(3), 66.

[60] Lu, H., Xi, D., Qin, G., 2023. Environmental risk of oil pipeline accidents. Science of the Total Environment. 874, 162386.

[61] Zhu, X., Venosa, A.D., Suidan, M.T., et al., 2001. Guidelines for the Bioremediation of Marine Shorelines and Freshwater Wetlands. US Environmental Protection Agency: Cincinnati, OH, USA.

[62] Zhang, Z., Du, Y., Lyu, Y., et al., 2025. An integrated mathematical modeling approach for reducing water footprint rate and carbon footprint intensity of Hanjiang River Ecological Economic Belt in China. Sustainable Water Resources Management. 11(6), 127.

[63] Yang, H., Shi, J., Lü, C., et al., 2026. Evaluation of water-economy-ecology system development level and coupling coordination degree: A case study of China's central plains urban agglomeration. Scientific Reports. 16(1), 14317.

[64] Wang, K., Zhang, L., Zhang, L., et al., 2020. Coupling coordination assessment on sponge city construction and its spatial pattern in Henan province, China. Water. 12(12), 3482.

[65] Yang, Y., Chen, J., Li, Z., et al., 2025. Coupling coordination of agricultural water-economy systems in China: Evidence from high-stress hydrological zones in a major grain-producing province. Frontiers in Sustainable Food Systems. 9, 1608329.

[66] Ndimele, P.E., Saba, A.O., Ojo, D.O., et al., 2018. Remediation of crude oil spillage. In: Ndimele, P.E. (Ed.). The Political Ecology of Oil and Gas Activities in the Nigerian Aquatic Ecosystem. Academic Press: London, UK. pp. 369–384.

[67] Lee, J.-H., Woo, H.J., Jeong, K.-S., 2018. Removal of non-aqueous phase liquids (NAPLs) from TPH-saturated sandy aquifer sediments using in situ air sparging combined with soil vapor extraction. Journal of Environmental Science and Health, Part A. 53(14), 1253–1266.

[68] Aelion, C.M., Kirtland, B.C., 2000. Physical versus biological hydrocarbon removal during air sparging and soil vapor extraction. Environmental Science & Technology. 34(15), 3167–3173.

[69] Di Stasio, L., Gentile, A., Tangredi, D.N., et al., 2025. Urban Phytoremediation: A Nature-Based Solution for Environmental Reclamation and Sustainability. Plants. 14(13), 2057.

[70] Alazaiza, M.Y., Albahnasawi, A., Ali, G.A., et al., 2021. Recent advances of nanoremediation technologies for soil and groundwater remediation: A review. Water. 13(16), 2186.

[71] Sharma, S., Shaikh, S., Mohana, S., et al., 2024. Current trends in bioremediation and bio-integrated treatment of petroleum hydrocarbons. Environmental Science and Pollution Research. 31(46), 57397–57416.

[72] Sulayman, H.O., 2019. Bioremediation of Spent Engine Oil in Some Selected Contaminated Soils [Master's Thesis]. Kwara State University: Ilorin, Nigeria.

[73] Adebajo, S.O., Akintokun, A.K., Ojo, A.E., et al., 2019. Biosurfactant production by rhizospheric bacteria isolated from biochar amended soil using different extraction solvents. Applied Environmental Research. 41(3), 72–82.

[74] Afzal, M., Yousaf, S., Reichenauer, T.G., et al., 2013. Ecology of alkane-degrading bacteria and their interaction with the plant. In: de Bruijn, F.J. (Ed.). Molecular Microbial Ecology of the Rhizosphere, Vol. 1. John Wiley & Sons, Ltd.: Hoboken, NJ, USA. pp. 975–989.

[75] Uba, B., Okoye, E.L., Dokubo, C.U., et al., 2018. Biostimulatory effect of organic and inorganic nutrients on soil biological indicators in diesel contaminated soil. Journal of Bioscience and Biotechnology. 3(6), 121–135.

[76] Vik, E., Bardos, P., Brogan, J., et al., 2001. Towards a framework for selecting remediation technologies for contaminated sites. Land Contamination and Recla-

mation. 9(1), 119–127.

[77] Zhang, M., Yang, S., Zhang, Z., et al., 2023. Development and application of an integrated site remediation technology mix method based on site contaminant distribution characteristics. Applied Sciences. 13(19), 11076.

[78] Suprenand, P.M., Hoover, C., Ainsworth, C.H., et al., 2019. Preparing for the inevitable: Ecological and indigenous community impacts of oil spill-related mortality in the United States' Arctic marine ecosystem. In: Murawski, S.A., Ainsworth, C.H., Gilbert, S., et al. (Eds.). Scenarios and Responses to Future Deep Oil Spills: Fighting the Next War. Springer: Cham, Switzerland. pp. 470–493.

[79] Hou, D., Al-Tabbaa, A., Hu, Q., et al., 2023. Sustainable remediation and redevelopment of brownfield sites. Nature Reviews Earth & Environment. 4(4), 271–286.

[80] Ellis, D.E., Hadley, P.W., 2009. Sustainable remediation white paper—Integrating sustainable principles, practices, and metrics into remediation projects. Remediation Journal. 19(3), 5–114.

[81] Zhang, Z., Sun, H., Guo, Y., 2024. The impact of marine oil spills on the ecosystem. International Journal of Engineering Sciences and Technologies. 2(1).

[82] Martinez Cruz, C.S., Cid Galiot, J.J., Márquez, A.E., et al., 2026. Techniques for Analyzing Soil Aggressiveness to Assess the Impact of Corrosion Using Artificial Intelligence on the Mechanical Integrity of Pipelines in the Oil and Gas Industry. Journal of Pressure Vessel Technology. 148(4), 040801.