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REVIEW

Advances in Transient Electromagnetic Methods for Field Investigation of Oil Pollution: A Comprehensive Review

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ABSTRACT

Transient electromagnetic methods are increasingly adopted for field investigation of oil pollution because they provide rapid, non-invasive imaging of subsurface electrical conductivity across depths relevant to vadose-zone impacts, groundwater plumes, and coastal transition zones. This review synthesizes recent advances that have expanded TEM (Transient Electromagnetic Method)'s environmental applicability, including higher dynamic range receivers, multi-moment acquisition that improves shallow-to-deep sensitivity, and diversified deployment platforms spanning ground, mobile/towed, airborne, and coastal/marine configurations, with emerging UAV (Unmanned Aerial Vehicle) options for constrained access. We emphasize the electrical and geochemical basis of hydrocarbon-related signatures, showing why fresh releases may appear resistive through NAPL (Non-Aqueous Phase Liquid) displacement of conductive pore water, whereas aged contamination often produces conductive responses driven by biodegradation, redox evolution, and elevated ionic strength. Because these responses are non-unique and can be confounded by clay-rich lithology, salinity gradients, temperature variability, and cultural infrastructure, contemporary interpretation has shifted toward process-consistent conceptual site models and uncertainty-aware products that communicate depth of investigation and resolution limits. A thematic synthesis of field applications indicates TEM is most reliable for mapping hydrogeological architecture, delineating plausible plume corridors, prioritizing intrusive sampling, and supporting monitoring where repeatability and background variability are controlled. The review concludes that TEM delivers the greatest decision value when integrated in a weight-of-evidence

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framework with hydrogeology, geochemistry, and targeted ground truth, and it highlights future needs in standardized reporting, robust time-lapse appraisal, and stronger petrophysical links to hydrocarbon transformation.

Keywords: Transient Electromagnetics; Oil Pollution; Conductivity Imaging; Biodegradation; Environmental Geophysics

1. Introduction

The oil and gas pipelines continue to be the global engine of transportation of energy and carry huge quantities of hydrocarbons over extensive geographical areas. Pipeline systems are normally thought to be more efficient and safer than other forms of transport, like road or rail, in the delivery of bulk energy[1]. However, the use of the pipelines is a major threat to the environment in the event of failures, especially in oil spills, leakages, and other related environmental upheavals. Such risks have increased the focus on the pipeline infrastructure by the people and their governments, leading to the growing focus on environmental stewardship in addition to operational efficiency. With the changing energy systems and stronger environmental regulation, the problem that pipeline engineering has to deal with is no longer just the maximization of the efficiency of the transport, but rather the compatibility of the efficiency gains with the long-term environmental protection[2,3].

Traditionally, the engineering research of pipeline has regarded efficiency and environmental protection as two distinct issues. Hydraulic performance, energy consumption, throughput capacity, and optimization of operations have been identified as the key efficiency attributes. On the other hand, environmental concerns have the usual focus on preventive spillage, environmental impact reduction, and regulatory requirements[4]. Nevertheless, there is an increasing amount of evidence that the two dimensions are closely intertwined as a result of recent studies. In the case of design decisions, operational strategies, and monitoring systems that enhance the efficiency of the system, environmental risk is likely to be affected. An example is how the size of the pipeline, routes, pressure, and the design of pump stations influence the energy usage as well as the stress distribution, the corrosion rate, and the probability of failure. On the same note, operational reliability and less unplanned downtime can be improved by ensuring strategies of integrity management that mitigate environmental risk, like enhanced inspection technologies or predictive maintenance systems. These communications suggest that engineering efficiency and environmental stewardship are not opposing priorities, but rather, they are complementary facets of the pipeline system operations[5–7].

This interdependence needs to be acknowledged through a change in thinking in which individual technological solutions are not considered independent but as part of a system. The concept of pipeline infrastructure is a complex engineered system, where design parameters, operational conditions, material degradation processes, monitoring technologies, and environmental effects interact with each other on various spatial and temporal levels. In these systems, the results of efficiency and the environmental performance are influenced by a set of decisions that are distributed through the lifecycle of the pipeline route selection and construction approaches to the sphere of operating and decommissioning procedures. Consequently, the enhancement of the environmental outcomes cannot be achieved only through downstream mitigation tools; upstream design optimization and constant monitoring of the system will be required as well. This combined approach has been gradually developing in the literature, yet it is still divided along disciplinary lines such as pipeline engineering, environmental management, corrosion science, and the development of monitoring technology[8–10].

The other key aspect that defines the modern studies in the area of pipeline is the growing complexity of operational environments. Most current pipeline networks are also located either in ecologically sensitive regions, hilly landscapes, or even in highly populated regions, with the aftermath of such leaks being especially detrimental. Meanwhile, the aging infrastructures in most countries are challenging the current integrity issues, such as corrosion, fatigue cracking, geohazards, and third-party interference. All these factors enhance the significance of proactive integrity management and real-time monitoring systems that can identify abnormalities before the environment is spoiled. New technologies of sensing, computerized monitoring, and digital infrastructure have thus been the main elements of contemporary pipeline management strategy. To improve the safety and environmental protection of the pipeline, fiber-optic sensing systems, satellite monitoring systems, unmanned aerial platforms, and data-driven diagnostic models are gradually becoming a part of pipeline operations [8,11,12].

In spite of these technological advancements, the research literature on the subject of engineering efficiency and environmental responsibility in pipeline systems is extremely scattered. Literature is replete with literature on particular technical aspects, including corrosion processes, leak detection algorithms, or hydraulic optimization models, but these works are not placed in the context of systems. As a result, although there is substantial knowledge on the issues that are faced by the individual engineering issues, there is a lack of studies that consolidate the interaction of these elements to form the general environmental performance. Lack of such synthesis prevents the researcher and practitioners from examining trade-offs between design choices, operational strategies, and monitoring technologies [13].

In addition, there are a number of crucial questions that have not been answered. As an example, the leak detection technologies have developed greatly, but it is observed that there remains a significant variation in the reported leak detection threshold, reaction time, and reliability under actual operating conditions. Likewise, the performance measures applied to assess the environmental effects, i.e., emission intensity, spill frequency, or ecological disturbance, tend to be mixed up in studies, and thus, cross-system comparisons cannot be made easily. The new technologies of the digital world, such as monitoring systems based on artificial intelligence and the concept of a digital twin, have potential solutions to these issues, and their implementation in the management of pipelines is only beginning to develop. Meanwhile, the increased impact of climate change also presents some new geohazard risks, including permafrost thaw, landslides, and flooding, which once again adds complexity to the issue of pipeline performance and environmental sustainability [13–15].

It is against this background that a detailed synthesis incorporating the engineering, environmental, and operational views is greatly needed. Such a synthesis cannot be a one-dimensional approach in which technological innovations are taken as an isolated solution, but it should consider how design decisions, operational approaches, integrity management approaches, and monitoring technologies generate a combined environmental impact of pipeline systems. These interactions are key to understanding how it is possible to find strategies that would improve the efficiency of operations and reduce ecological risk at the same time.

The review thus looks at the changing relationship between the efficiency of engineering and the environmental stewardship of the oil and gas pipeline systems. The main thesis presented in this article is that these two goals are not autonomous but are instead regulated by a system-wide set of decisions in which there are infrastructure design, operational management, integrity assurance, and monitoring capability. The proposed review will be informed by using this integrated lens to examine the current literature to clarify the scope of engineering practices on environmental outcomes and highlight the aspects in which technological advancement can help enhance not only efficiency but also sustainability.

And the rest of this paper is structured on this system-oriented point of view. To begin with, the theoretical connection between efficiency and environmental stewardship is investigated to develop a framework within which the interaction between the two in the pipeline systems can be understood. The following parts examine how the design and operational choices affect the performance of the system, and finally, integrity management strategies are discussed to connect reliability and environmental protection. The review then rates monitoring and leak detection technologies as essential levels of environmental protection. Lastly, the general lifecycle effects of pipeline infrastructure and future technological trends are combined to pinpoint research gaps and future trends. It is with such a combined examination that the review aims to add a clearer insight into the potential of engineering innovation to assist with the development of pipelines in an environmentally responsible manner in an ever-changing energy market [16–19].

2. Electromagnetic and Geochemical Basis of Oil-Pollution Signatures

Transient electromagnetic methods respond primarily to the subsurface distribution of electrical conductivity, which in environmental settings is controlled less by the intrinsic properties of the solid matrix than by the ionic content, connectivity, and saturation state of pore fluids [20]. Because petroleum hydrocarbons are typically electrically insulating, the presence of oil alone does not guarantee a distinctive electromagnetic response. Instead, oil pollution produces a spectrum of signatures that reflects multiphase fluid distributions, lithologic contrasts, and critically, the coupled biogeochemical processes that modify groundwater chemistry over time. A rigorous interpretation, therefore, requires linking the measurable conductivity structure to plausible contaminant states and transformation pathways, rather than treating conductivity anomalies as direct proxies for hydrocarbon mass.

2.1. Electrical Conductivity in the Shallow Subsurface: Dominant Controls

In unconsolidated sediments and weathered rock, bulk electrical conductivity is determined by two principal pathways: electrolytic conduction through interconnected pore water and surface-related conduction associated with mineral–fluid interfaces. In clean sands and gravels with low clay content, electrolytic conduction dominates and is strongly governed by porosity, water saturation, and the ionic strength of groundwater. Under these conditions, relationships analogous to Archie-type behavior provide a useful conceptual foundation: conductivity decreases as pores become less water-filled, and increases as pore fluid salinity rises, with the magnitude of change depending on how well pore space remains connected[21].

In fine-grained or clay-bearing materials, the picture changes because surface conduction can become significant, sometimes dominant. Clay minerals and other reactive surfaces can host electrical double layers and exchangeable ions that contribute to conductivity even when pore water salinity is modest. This has two consequences for oil-pollution investigations. First, high conductivities may reflect lithology rather than contamination, particularly where clay lenses, paleosols, or weathered horizons are present. Second, the sensitivity of bulk conductivity to changes in pore fluid chemistry may be damped or complicated in clay-rich media because surface conduction can mask fluid-driven variations. Temperature is an additional control, especially in shallow zones and seasonal climates, because ionic mobility increases with temperature; this can create apparent conductivity changes unrelated to contamination or remediation. Together, these controls mean that conductivity anomalies become interpretable only when placed in a stratigraphic and hydrogeological context[22,23].

2.2. Hydrocarbon Phase Behavior and the Direct Electromagnetic Effects

Oil releases commonly generate non-aqueous phase liquids (NAPLs) that partition into light (LNAPL) and dense (DNAPL) behavior depending on composition and density relative to water[24]. From an electromagnetic perspective, the most intuitive "direct" effect arises when electrically insulating NAPL displaces conductive pore water and reduces electrolytic pathways. In clean, water-saturated sands, a NAPL-impacted zone can therefore appear resistive relative to background, particularly when LNAPL accumulates near the capillary fringe or when DNAPL pools atop low-permeability units. This resistive response is most likely to be observable when the background geology is not already resistive and when the saturation contrast is spatially coherent at a scale resolvable by the measurement footprint.

However, the direct resistive signature is neither universal nor stable. NAPL distributions are often discontinuous, controlled by capillary entry pressures, stratigraphic heterogeneity, and preferential pathways, producing patchiness that may be below the effective resolution of field-scale TEM. Moreover, vadose-zone conditions can yield resistive anomalies unrelated to hydrocarbons because drying, coarse fill, or man-made materials can also reduce bulk conductivity. In coastal and nearshore environments, strong salinity-driven conductivities can overwhelm modest resistive contrasts produced by NAPL. As a result, while resistive features are commonly discussed as potential indicators of NAPL, their diagnostic value increases substantially when corroborated by site history, borehole observations, and hydrogeological plausibility[25].

2.3. Biogeochemical Transformation and the Indirect Conductivity Responses

The prevailing electromagnetic signature in the contaminated sites is not necessarily the oil phase, but secondary geochemical signatures that are caused by biodegradation and redox evolution in many contaminated sites. With hydrocarbons being broken down by microorganisms, terminal electron acceptors like oxygen, nitrate, manganese (IV), iron

(III), sulfate, and carbon dioxide can be used up in order, resulting in reducing conditions that transform the stability of minerals, the availability of ions, and aqueous chemistry. Such reactions tend to raise the ionic strength of the groundwater by the generation and mobilization of dissolved species, and raise bulk conductivity within and around affected areas.

Its spatial expression is often based on the idea of a conductive halo or plume fringe around a more resistive core, or a conductive downgradient zone linked to a dissolved-phase transport and biodegradation fronts. But this tendency is not even sure. The orientation and intensity of conductivity variation vary with the original groundwater chemistry, buffering power, mineralogy, and hydrologic flushing. In other environments, biodegradation may cause the precipitation of secondary minerals that alter the pore structure and could decrease its permeability, which results in complex and even counterintuitive electrical results. Also, remediation processes can introduce powerful conductivity disturbances that can prevail over the natural biogeochemical recording. Amendments, nutrients, or oxidants may be injected temporarily to raise the conductivity due to added ions, whereas saturation fields and temperature fields may vary as a result of air sparging or aggressive pumping. Thus, indirect signatures tend to be the most observable and at the same time the most interpretively subtle, in which you need to carefully differentiate the contamination-induced processes from operation artifacts [26].

The range of resistive and conductive responses observed at hydrocarbon sites can be summarized using process-consistent conceptual models that distinguish fresh NAPL impacts from mature, biodegradation-dominated plumes (**Figure 1**).

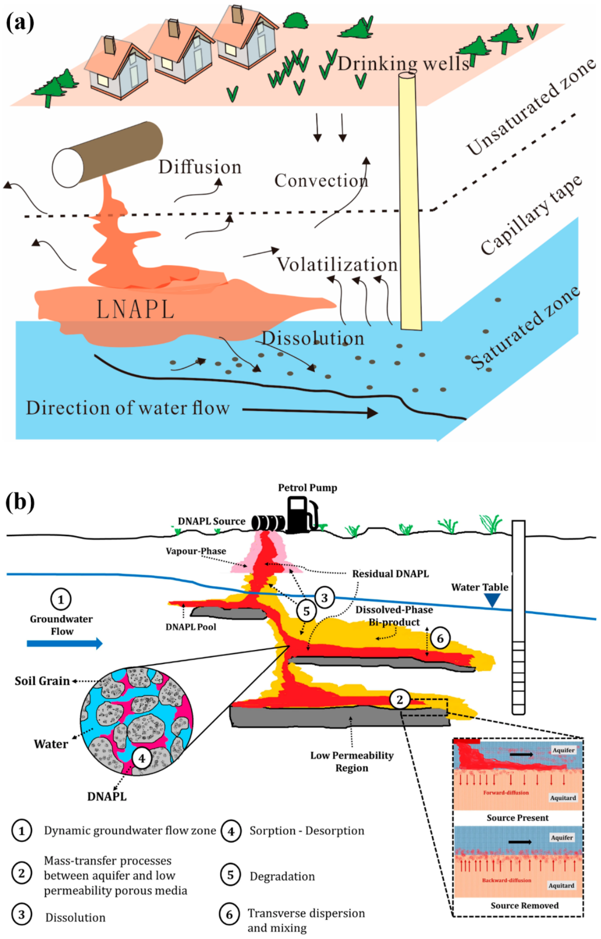

Figure 1. Conceptual evolution of oil pollution and corresponding TEM-relevant conductivity patterns. Schematic cross-sections illustrate: (**a**) early-stage releases dominated by LNAPL redistribution and saturation effects that may produce localized resistive zones [27]; (**b**) mature stages (DNAL) where biodegradation and redox evolution can increase ionic strength and produce conductive halos and downgradient conductive corridors [28].

Note: The figure emphasizes geometry and stratigraphic position (e.g., capillary fringe, low-permeability barriers, transmissive layers) as primary interpretive cues rather than conductivity magnitude alone.

2.4. Spatial and Temporal Evolution of Signatures: From Fresh Releases to Mature Plumes

Signatures of oil-contamination change over time and space, which represent the movement of a source-dominated system to a system of transport and transformation[29]. Soon after a release, localized deposits of NAPL and high saturation differences locally at the place of release and along preferential flow numbers may dominate the subsurface. Mass is redistributed to groundwater over time through weathering processes and to the chemistry of aquatic environments and redox processes through biodegradation. This development is prone to expanding the spatial extent of conductivity aberrations, occasionally relocating detectability concerning a compact resistive body towards larger patterns of conductivity trends in distinct and prolonged patterns with the groundwater.

This complexity is induced by environmental heterogeneity. Stratigraphic layers are capable of entrapping NAPL, establishing perched layers, diverting dissolved plumes, and causing conductivity patterns that are both elongated, stratigraphically localized, or laterally discontinuous. NAPL may be mobilized and immobilized seasonally by groundwater effects, and the capillary fringe may become thin and thick, and the dissolved constituents may be diluted. Freeze-thaw cycles in cold climates may redistribute moisture and cause very intense seasonal changes in conductivity that may simulate or obscure the effects of contamination. These relations explain why unidimensional interpretation with reference to one survey may easily be weak; strong knowledge can be found in the synthesis of conductivity structure with time-dependent site data, and, where possible, repeated measurements[30].

Since conductivity responses change with hydrocarbon phase redistribution and biogeochemical transformation, interpreters should be aware of many potential types of signatures and confounders. The dominant controls, expected tendencies, and validation pathways are summarized in **Table 1**[31].

Table 1. Electrical and Geochemical Controls on TEM Signatures of Oil Pollution and Major Confounders.

Dominant Site Process/State	Expected Conductivity Tendency	Typical Spatial Expression in TEM Models	When this Signature is Most Plausible	Major Confounders (Non-Hydrocarbon)	Validation that Most Increases Confidence
NAPL displacing conductive pore water (fresh release; clean sands)	More resistive	Localized resistive body near capillary fringe or atop low-permeability unit	Low-clay, water-saturated media; clear stratigraphic trap	Dry vadose zone, coarse fill, shallow bedrock, engineered road base	Soil cores for NAPL, LIF/screening tools, lithology + moisture/saturation context
Biodegradation increasing ionic strength (aged plume; redox evolution)	More conductive	Conductive halo around source and/or conductive downgradient corridor	Evidence of reducing conditions; transmissive pathways	Clay-rich layers, landfill leachate, road salt impacts, industrial brines	Major ions/TDS, redox indicators (DO, Fe/Mn, sulfate), alkalinity, temperature
Salinity intrusion/mixing (coastal transition)	Strongly conductive	Large-scale conductor structured by tides and hydrostratigraphy	Coastal aquifers; nearshore sediments	Often indistinguishable from contamination without context	Salinity (EC/Cl^-), tidal stage info, coastal hydrogeology, pore-water sampling
Remediation amendment injection (nutrients/oxidants/ionic amendments)	Conductivity increases (often transient)	Local conductor near injection wells expanding along flow	Active treatment; known injection geometry	Seasonal groundwater changes; temperature effects	Injection logs, ion chemistry time series, paired well monitoring + repeatable survey lines
Dilution/flush-out or plume stabilization	Conductivity decreases or pattern stabilizes	Reduced conductivity magnitude or shrinking conductive corridors	Sustained pumping/flush or natural attenuation	Seasonal variability; survey repeatability errors	Groundwater levels, temperature, repeated geochemistry, repeatability checks

2.5. Non-Uniqueness and Confounding Factors in Conductivity-Based Interpretation

Making use of TEM to oil pollution is dominated by one principal difficulty: non-uniqueness: various geological or environmental events will create comparable conductivity structures[32]. Stratigraphy Clay-rich stratigraphy Conductive anomalies that mimic the appearance of biodegradation halos or dissolved hydrocarbon plumes may be caused by clay-rich stratigraphy, saline intrusion, landfill leachate, road salt impacts, septic effluent, and industrial brines as well. On the contrary, resistive anomalies may be given due to dry sands, coarse gravels, competent bedrock, engineered fill, buried infrastructure, or low-porosity units, any of which would be wrongly interpreted as NAPL without its context.

A coastal environment is especially vexed as coastal sea salinity has a first-order effect on conductivity, and the land-sea interface may contain sharp gradients, which control electromagnetic responses. Cultural noise and metallic objects that are beneath the ground, which can set off this ambiguity, are introduced by urban and industrial settings and may interfere with measurements and model interpretation[33]. Notably, it is not only that these confounders are noise, but that they are arguably just alternative explanations that need to be explored. To make such a review oriented to field investigation, it implies that the probabilities of conductivity anomalies being evidence of perturbed subsurface electrical properties must be probabilistically and conditionally formulated: under some constraints of hydrogeochemical and lithological conditions, oil-related processes can be the cause of such anomalies.

2.6. Implications for TEM Use in Oil-Pollution Investigations

The interpretation idea based on the changing nature of conductivity caused by oil pollution implies that a strategy of interpretation should be based on pattern-consistent process-based change and not based on individual threshold values[34]. TEM is currently in the best position to map the geometry of conductive and resistive domains, stratigraphic controls on flow, and spatial relationships that are consistent with the anticipated behavior of contaminants, i.e., downgradient conductive trends in environments where biodegradation is increasing ionic strength, or isolated resistive bodies where NAPL is likely to be expelling pore water in clean sediments. The most justifiable inferences are the ones that are consistent with a conceptual site model, which includes the lithology, groundwater gradients, salinity regimes, and reasonable reaction pathways, and which can be supported by selective ground truth.

It is also this electrical and geochemical framing that explains why the integrative approach can be required[35]. TEM can locate the locations of conductivity structure transitions, and plume-scale distortions may be, but usually cannot, on its own establish the presence of hydrocarbons, or determine the amount of hydrocarbon mass. The contribution of TEM to the work on oil pollution is thus initially purely spatial, which is constrained: it reduces the uncertainty in the structure of the subsurface, emphasizes areas of congruence to processes of contamination, and aids in efficient targeting of chemical and hydrogeological tests. This conceptual foundation, in the following sections, offers the framework through which developments in instrumentation, deployment, practice of interpretation, and field evidence can be evaluated in the context of their impact on the application of the outcomes of detection, delineation, and monitoring.

3. Advances in TEM Systems and Field Deployment for Environmental Work

The empirical significance of the transient electromagnetic processes in oil-pollution studies is closely linked to the way the instrumentation creates the transmitter moments, whether it is the fidelity in the wide dynamic ranges of the receivers, and the ability of survey platforms to provide repeatable coverage in difficult operating conditions[36]. Development of TEMs in the environmental field over the last one decade has been guided by a set of field considerations stable over the years: it is desired to image both shallow and deep structure of conductivity without loss of depth information, in a manner that offers reliable operation during cultural electromagnetic noise, acquisition time needs to be reduced without loss in data quality and spatial positioning and repeatability that conductivity images can guide decision and, with growing popularity, monitoring. Such requirements have spurred concurrent developments in ground, mobile/towed systems, airborne TEM, and coastal or maritime deployments, and also new developments with UAV-enabling of acquisition. What you will not get is merely improved equipment, but an expanded operational space within which one can reasonably expect the operation of TEM in the heterogeneous, infrastructure-covered, and limitation-prone environments of oil-contamination sites. These advances in ground systems, mobile/towed systems, airborne TEM, and UAV-enabled acquisition have greatly extended the operation scope of TEM in harsh environments such as oil-contaminated environments, as shown in **Figure 2**[20,37,38].

3.1. Ground TEM: From Site-Specific Soundings to High-Throughput Environmental Mapping

The ground-based TEM continues to form the basis of investigations of contaminated land due to its flexibility in geometry, the possibility to control transmitter and receiver configurations, and the ability to customize measurements to small footprints around infrastructure[20]. One trend has been the consistent replacement of point-by-point surveys with single-sounding surveys that retain the capacity to resolve shallow layers. The enhanced receiver electronics and ergonomics of the system have resulted in less setup time and higher productivity, and have made it possible to gather denser grids that represent heterogeneity better and minimize the possibility of missing narrow slits. This reversal is especially noteworthy at oil-influenced locations where there is a permit contrast, buried utilities, and engineered fill may cause intense lateral variability over limited ranges.

Simultaneously, ground TEM has been extended to a variety of loop sizes and moments, which can be adjusted to the size of the problem[39]. Small loop and compact systems are now more convenient in shallow and high-resolution imaging of industrial footprints, to large loop designs when one needs the depth penetration to identify confining units, underlying topography, or deeper plume movement. The implications for oil-pollution field work are an increased ability to scale TEM: a site can be screened with large footprints at a rapid rate and then narrowed down in the area with smaller loops and closer line spacing, without terminating the TEM modality.

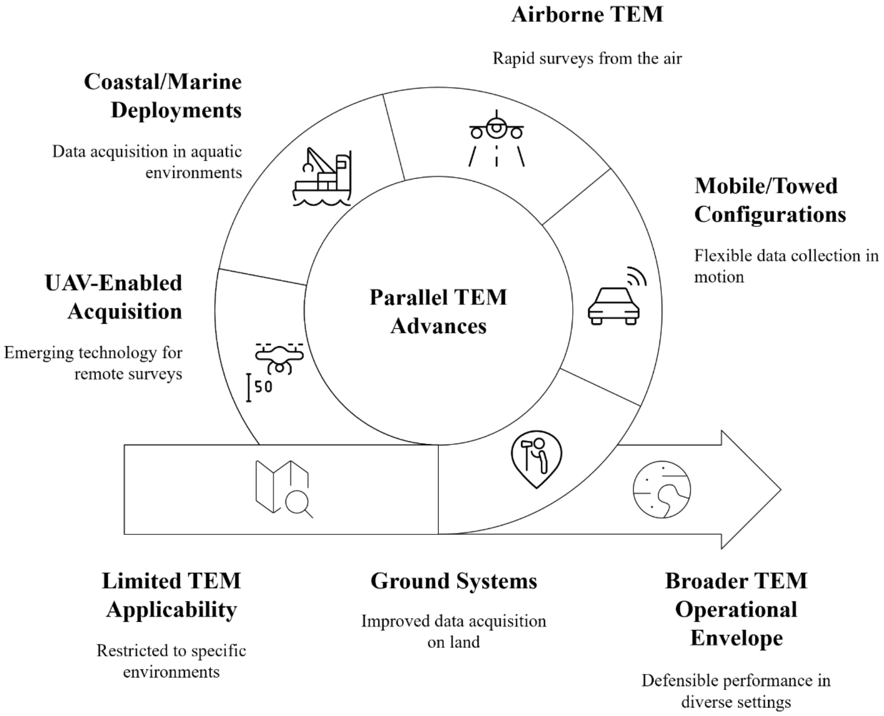

Figure 2. TEM Advances.

Note: Recent TEM technology development, ground systems, mobile/towed systems, airborne TEM, and UAV-facilitated acquisition have extended the operational footprint of TEM and enabled its deployment in heterogeneous and infrastructure-saturated and safety-constrained environments such as those found in oil-contaminated sites.

3.2. Expanded Dynamic Range and Multi-Moment Acquisition for Shallow Deep Coupling

Another of the most impactful instrumental developments on environmental TEM has been the enhanced capability to record early-time and late-time responses with a signal-to-noise ratio to make use of[40]. The investigation of oil-pollution often necessitates both a surface sensitivity, close to the near-surface of the oil-anticipated NAPL in the vadose zone or near the capillary fringe, and a deeper groundwater sensitivity, where dissolved-phase transport and biogeochemical modification can be the order of the day. In the past, there might have been a tradeoff between these requirements: Deep-optimized instrumentation systems would have poor chances of maintaining early-time stability and saturation, whereas shallow-based designs would be poor at strong effects.

This is being handled by modern systems with extended dynamic range receivers, better timing control, and multi-moment acquisition strategies, which combine transmitter moments or waveforms in a single survey. Higher moments improve the late-time performance of detecting deeper structures, whereas lower moments have the ability to maintain the early-time performance of shallowly layered structures. Properly done, this saves the operational cost of conducting separate surveys of shallow and deep targets and enhances the internal consistency of shallow and deep interpretation. In the case of oil sites, where a resistive layer affected by NAPL can be offset by a conductive biodegradation halo at other depths, the capacity to record both regimes in the same data set is especially useful in that it allows one to interpret the data based on consistent vertical structures instead of isolated slices[41].

3.3. Continuous Profiling and Mobile/Towed TEM in Industrial and Corridor Settings

The second significant trend has been the maturation of mobile and towed TEM designs that are used in continuous profiling[42]. The purpose of the investigation of oil infrastructure is commonly to locate localized anomalies through a long alignment of pipeline, access roads, coastal protection, and utility easements, where the investigation goal is to locate local anomalies and not attribute multivariate characteristics to a small site. Stop-and-go ground soundings may be operationally inefficient in such situations, and a real risk is that spatial aliasing may take place when the sampling density is low. Continuous systems deal with these limitations by providing quasi-continuous measures with constant geometry to permit the structure of conductivity to be mapped as a function of distance, with a far greater level of spatial granularity.

This method is particularly useful in the identification of stratigraphic variations that can govern migration, e.g., the passage between coarse and fine sediments, the presence of highs in the bedrock that can alter the direction of flow, or a conducting object that can mark the presence of dissolved-phase effects[43]. Speed is not the only field value; continuous profiling also gives extra support to more systematic repeat surveys, as the platform geometry and positioning can be reproduced with decreased degrees of freedom. However, the configurations also bring different disadvantages, such as the noise caused by motion, unreliable coupling with the ground, and vulnerability to metallic infrastructure. These problems have been reduced by improvements in mechanical design, synchronization, and positioning, but interpretation in industrial corridors remains a valuable subject of taking care that cultural artifacts are not overrun, and that conductive responses may be caused by buried metal rather than underground fluids.

3.4. Airborne TEM: Regional Context, Rapid Screening, and Environmental Resolution

Airborne TEM has transformed the way in which environmental characterization on a regional scale is expected to be carried out by facilitating the rapid mapping of conductivity structure over hundreds of thousands of square kilometers[44]. Though naturally related to the exploration of minerals and groundwater, airborne systems have also proven useful to environmental issues, with a requirement to know the hydrogeological structure as much as to identify contamination. In oil-pollution studies, airborne TEM commonly provides a major contribution of contextual nature, in that it defines conductive and resistive domains which are informative of lithology, salinity distributions, aquifer geometry, and the confining structures, and constraining plausible contaminant migration pathways, as well as distinguishing site-related anomalies and more general natural variability.

Recent developments have enhanced the applicability of airborne TEM to shallow environmental targets by enhancing system calibration, stability, improving the ability of the system to process early-time data, and optimizing navigation and altitude control. Such enhancements are expressed as improvements in the near-surface sensitivity and minor improvements in detecting shallow layers of conductivity, important when determining oil contamination in coastal plains, deltas, and other environments where the most important stratigraphy can be found within the surface tens of meters. Airborne TEM finds application in the spill response or screening of the region where time is of the essence and access is limited; areas where detailed ground surveys and sampling should be focused on can be identified quickly. Nonetheless, TEM by air is limited by its footprint and by the interpretive preeminence of large-scale geologic and salinity impacts; that is, it is generally supportive and not displacementary of ground studies in which the choice is fine-scale delimitation around sources[44].

3.5. Coastal and Marine TEM: Working across Highly Conductive Water and the Land–Sea Transition

Coastal oil pollution presents a distinct electromagnetic challenge because seawater is highly conductive and can dominate TEM responses, especially in shallow-water environments where the water column thickness and salinity variability interact with seabed properties. The land–sea transition zone adds further complexity through rapid changes in saturation, lithology, and anthropogenic structures. Advances in coastal and marine TEM have therefore focused on configurations and processing strategies that preserve sensitivity to the seabed and shallow sub-seafloor in the presence of a conductive water layer, and on amphibious approaches that can maintain interpretive continuity across shoreline boundaries[45].

Progress in this area has been enabled by improved platform stability and positioning, better characterization of the transmitter waveform and system response, and a growing body of field experience that clarifies where and how TEM can resolve sub-seafloor conductivity contrasts in conductive environments. For oil-pollution investigations, these developments matter because nearshore contamination often involves both terrestrial and marine processes, including tidal pumping and salinity mixing that can mimic contamination-related conductive halos. Marine and coastal TEM can contribute by mapping the geometry of conductive sediments, identifying freshwater–saltwater interfaces, and detecting anomalies consistent with altered pore-fluid chemistry, but it must be interpreted with careful attention to hydrodynamics and salinity structure[46,47].

3.6. UAV and Emerging Lightweight Platforms: Promise and Practical Boundaries

TEM is also a possible application of UAVs that has been proposed as a transition point between ground-based and conventional airborne surveys, as it can be deployed quickly and can reach dangerous or challenging areas without the logistical overhead of manned aircraft. The key technical constraint has been payload: meaningful TEM depth penetration requires transmitter moment, and transmitter moment requires coil size, current, and power; small UAVs have problems with all of them. Therefore, UAV TEM remains most viable in shallow targets and screening small areas as opposed to deep imaging or large-scale mapping at the moment[38].

Even within these boundaries, incremental advances in lightweight coils, power management, vibration isolation, and navigation are expanding the set of plausible applications. For oil-pollution work, UAV TEM may prove most useful where access is constrained by wetlands, unstable ground, steep shorelines, or safety restrictions near active facilities, and where the target of interest is shallow[48]. Its broader adoption will depend on demonstrating repeatability, managing motion-related noise, and clarifying regulatory and safety frameworks for operating in industrial environments. As with other platforms, the key criterion for environmental relevance is not novelty but whether the platform produces stable, interpretable conductivity images with well-characterized uncertainty.

3.7. Operating in Cultural Noise: Instrument Robustness, Positioning, and Practical Field Reliability

Oil-pollution studies are often conducted in the electromagnetically noisy oil refineries, terminals, pipeline corridors, urban brownfields, and coastal infrastructural regions[48]. TEM measurements can be distorted by cultural noise caused by power lines, electric rail, pumps, cathodic protection systems, fences, and buried utilities, particularly at early times. Hardware development has counteracted this partially with better shielding, better receiver linearity, and increased timing stability, as well as in practice reliability with field strategies that either control the noise sources or else characterize them. The latest systems are becoming actively integrated with a more accurate GNSS/INS positioning and with a larger time synchronization, and with even better metadata recording, all of which assist in quality control as well as repeat survey.

Positioning and repeatability have been given a more prominent place as environmental stakeholders are expecting geophysical outputs to be similar over time, rather than just interpretable at a single time. To monitor and ensure remediation, small positioning errors may conceal the conductivity variations if the subsurface is nonhomogeneous. Better navigation and standardized acquisition protocols are thus a silent major step forward in the practice of deployment, which allows more defensible change detection and allows the integration of TEM results with borehole and sampling datasets, which are naturally spatially referenced[32,49].

3.8. Implications for Oil-Pollution Field Investigations

All these systems and deployment advances increase the contribution of TEM to the practice of contaminated sites. Compared to air TEM, Ground TEM is better suited to shallow sensitivity and productivity, which is better able to characterize dense site-scale near sources and infrastructure. Mobile and towed designs enhance coverage in linear assets in order to provide repeatable profiling in hotspots where quick identification of hotspots is vital. Airborne TEM offers a regional hydrogeological setting and screening capacity that can radically reduce the duration between uncertainty and targeted inquiry, especially for large or inaccessible scales. Developments of coastal and marine TEM enhance continuity on the environments that are often most ecologically sensitive but also most challenging of electromagnetism over which oil impacts are most affected. The future directions of the UAV platforms are the way forward in quick, shallow screening in confined or dangerous terrains. To facilitate the practical project planning, platform selection needs to occur as a trade-off between the depth reach, resolution, access, noise sensitivity, and monitoring repeatability. These deliberations and optimal fit deliverables to typical TEM deployments are summarized in **Table 2** [20,50].

Meanwhile, these progresses do not rule out the inherent interpretive limitations mentioned in Section 2. Greater detail can be brought to light with better instruments, yet the conversion between the conductivity structure and contamination state is conditional and context-dependent. Practical consequence is thus best described as an increased capability to map and track conductivity in the environments where oil pollution takes place, with a greater operational viability and repeatability. This paves the way to the following section, where the focus switches to the deployment of TEM to how interpretive practice has been changed to bring out contamination-relevant understanding in dealing with ambiguity and uncertainty.

Table 2. TEM Platforms for Oil-Pollution Field Investigations: Capabilities, Constraints, and Best-Fit Use Cases.

TEM Platform/Configuration	Typical Investigation Scale	Practical Depth Reach (Site-Dependent)	Strengths for Oil-Pollution Work	Common Constraints in Real Sites	Best-Fit Deliverables
Ground TEM (small/medium loops)	Site scale (tens–hundreds of m)	Shallow to moderate	Flexible geometry near infrastructure; good for source-area refinement and stratigraphic control	Cultural noise; access limitations; interpretation confounded by fill/metal	Depth-to-water table proxies, shallow layering, anomaly boundaries for targeted sampling
Ground TEM (large loops/high-moment)	Site to local catchment	Moderate to deeper	Better late-time sensitivity for deeper aquifer architecture and confining units	Larger footprint reduces lateral resolution; setup time	Aquifer geometry, confining layer continuity, deeper plume corridor constraints
Mobile/towed TEM (continuous profiling)	Linear assets (km-scale)	Shallow to moderate	High spatial sampling along corridors; improved repeatability for monitoring lines	Motion noise; coupling variability; pipeline/metal artifacts	Corridor segmentation, hotspot flagging, prioritized follow-up transects
Airborne TEM (AEM)	Regional (tens–1,000s km^2)	Moderate (environmental focus)	Rapid screening; regional hydrogeological context; salinity and lithologic domain mapping	Larger footprint; logistics; contamination attribution is indirect	Hydrogeological framework maps, salinity architecture, target prioritization for ground follow-up
Coastal/marine TEM	Shoreline to nearshore	Shallow to moderate beneath seabed	Works across land–sea transition; supports shoreline/oiling context	Seawater conductivity dominates; hydrodynamic variability	Fresh–salt interface constraints, seabed domain mapping, shoreline transition continuity
UAV/lightweight TEM (emerging)	Small sites/difficult terrain	Shallow	Rapid deployment; access to hazardous or soft ground	Payload limits reduce transmitter moment; motion noise	Rapid shallow screening, reconnaissance of constrained zones

4. Integrity Management, Leak Detection, and Lifecycle Environmental Stewardship

The pipeline environmental performance is not limited to the effectiveness of hydraulic but also includes the effectiveness of infrastructure integrity, release detection, and lifecycle environmental impacts management. The management of integrity reduces the likelihood of failures, anomalies in a monitoring system are spotted and assist in responding quickly, and the lifecycle planning identifies the overall environmental impact of pipeline systems. They are interdependent elements that work as an integrated system where prevention, detection, and mitigation can influence the environmental outcomes[51]. This decision-oriented progression from conceptual site model to action is summarized in **Figure 3**.

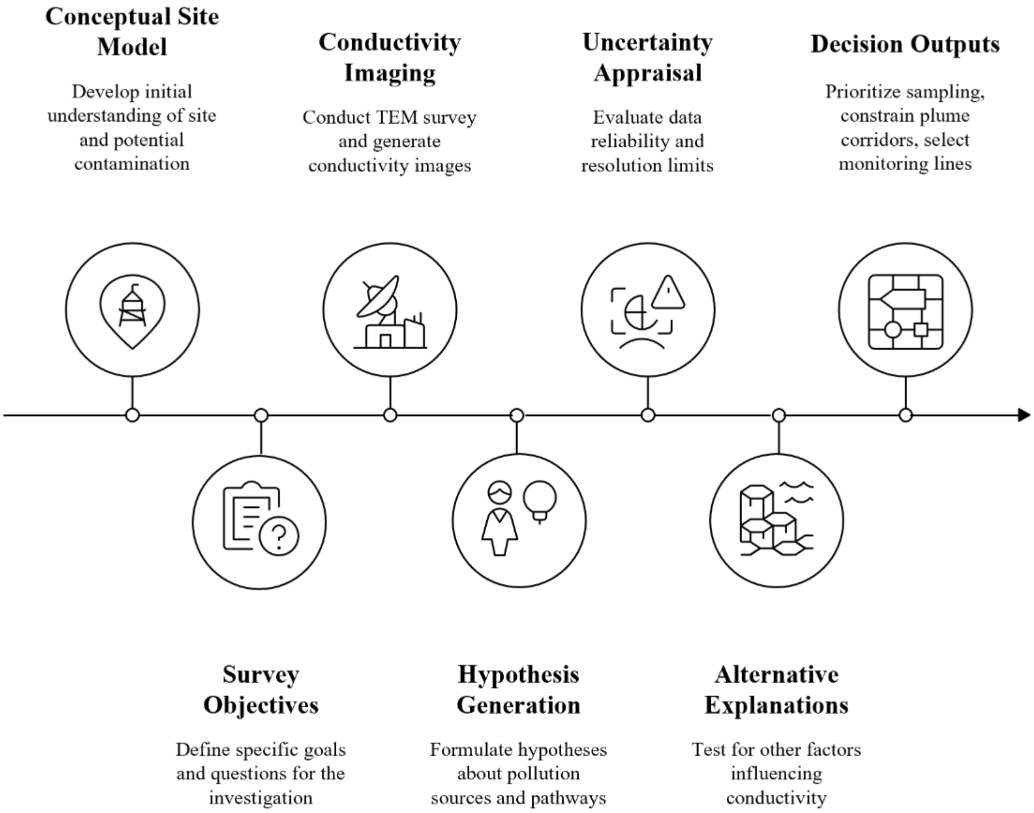

Figure 3. Interpretation-to-Decision Workflow for Oil-Pollution Investigations Using TEM.

4.1. Integrity Management as a Foundation of Environmental Stewardship

The concept of pipeline integrity management is usually discussed as a field of safety, but it is also the key to defining the efficiency of operation and environmental risk. The degradation processes, like corrosion, cracking, mechanical, and geohazards, enhance the risks of leakage or rupture and compel the operators to operate with a conservative operating point, to reduce throughput, or to perform disruptive maintenance operations. Such reactions may amplify the energy usage and working emissions. In turn, the quality of integrity programs leads to a decrease in the probability of failures and operational inefficiencies because pipelines are able to run near optimum design parameters and have additional confidence in the safety margin.

Contemporary integrity management is often carried out by the lifecycle method, which includes threat detection, evaluation of the risk, prevention strategies, inspection, and specific mitigation actions. Although the particular priorities used with gas, liquid, and offshore pipelines differ, the basic goal is the same: the degradation must be controlled to ensure that the pipeline can provide a continuous service for decades without making the risk of failures unacceptably high[52].

One of the most common threats to the integrity of pipelines is corrosion. Recovery of coating, efficiency of cathodic protection, soil chemistry, moisture, and stray electrical currents have an effect on external corrosion. Internal corrosion, on the other hand, is encouraged by the accumulation of water, dissolved gases like CO_2 and hydrogen sulphide, microorganisms, and the conditions of operation that enable the corrosive conditions to develop. Threats associated with cracking, such as stress corrosion cracking, hydrogen-assisted cracking, and fatigue, may develop without apparent hydraulic evidence to the point of critical defect sizes. Excavation damage or strain as a result of geohazards only adds to the chances of failure. The significance of these degradation processes acts in spreading the importance of preventive strategies in the form of coating, cathodic protection, internal corrosion control, and consistent inspection programs.

Integrity management thus serves as a stabilizing tool in the pipeline systems. The decreased uncertainty with regard to asset condition and degradation rates would also allow the operators to prevent over-derating the asset or to undertake frequent interventions, which would otherwise raise the cost and disturbance of the environment. In this regard, the management of integrity serves as an interface with reliability, efficiency, and environmental stewardship [53].

4.2. Leak Prevention, Detection, and Response Systems

Although integrity management limits the chances of failure, to ensure that releases do not occur even after preventive controls, there should be monitoring systems. The number of events that may cause leaks in the pipeline is very broad, as it may be corrosion defects, crack propagation, gasket failures, mechanical damage, or strain caused by geohazards. Such failures can result in chronic low-rate leaks or high-rate ruptures, which have different environmental risks and detection problems.

The effect of the product on the environment depends not only on the quantity of the product discharged but also on the product release rate, the time of detection, the isolation capacity, and the sensitivity of the site. Quick identification and isolation are thus essential elements in successful environmental protection measures. The level of spills in the case of liquid pipelines is dependent on the remaining inventory between isolation valves, whereas in gas systems, the blowdown approach affects the level of methane emissions and safety hazards [54].

Prevention measures are a complement to the integrity management as they minimize the chances of defects developing into substantial releases. The design decisions (valve spacing, automated shutdown system, and station containment measures) can greatly mitigate the spill impacts by minimizing the release time and giving an opportunity to respond promptly. It also depends on the release probability of the operational practices. Both efficient pressure management and formal excavation control programs can be used to decrease fatigue loading and crack growth and minimize third-party damage. Minimization of blowdowns and vented gas capture are also operational strategies that can be used in gas pipelines to cut methane emissions [55].

The next line of defense is represented by detection technologies. The SCADA-based computer pipeline monitoring systems are also still popular due to the fact that they offer continuous coverage of extensive pipeline sections. These systems are simple mass-balance systems up to sophisticated real-time transient model systems that compare desired and actual hydraulic behavior to detect anomalies. The performance of detection is, however, very sensitive to the accuracy of measurements, telemetry latency, and model calibration. The sensitivity tends to increase, leading to an increase in false-alarm rates, whereas conservative alarm levels will likely delay the detection of small leaks. Deployment thus needs to be tuned continuously, integrated in operation, and have sound alarm-management practices.

Modern detection strategies are also turning towards layered monitoring architectures, as there is no single monitoring approach that provides full coverage. SCADA-based surveillance is capable of providing a wide view of system surveillance, whereas fiber-optic monitoring or acoustic surveillance offers a fine-scale view of critical segments. Independent screening is offered by aerial/satellite monitoring on a large area, and specific sensors can be used on the facilities to detect emissions. The goal is not to depend on one technology, but rather to establish a combined monitoring network that is useful in giving dependable detection and facilitating quick response measures [56].

4.3. Lifecycle Environmental Impacts and Mitigation

The concept of environmental stewardship in the pipeline systems goes beyond the operational emissions and leakage to include the entire infrastructure lifecycle. The effects on the environment are experienced in the planning, building process, operation process, maintenance, and decommissioning process, and most of them are also influenced by early design decisions, like the routing process and the placement of the stations[57].

The disruption of ecosystems by the construction activity may include land clearing, excavation of the soil, and installation of a water crossing. These disturbances are not always permanent, but the ability to restore the situation requires the long-term monitoring and maintenance of the right-of-way conditions. There are also environmental impacts arising from the operation activities, which include pumping and compression stations, energy-related emissions, facilities, noise and air, and periodic disturbances generated by maintenance or integrity interventions.

Geohazards associated with climate are the ones that are increasingly affecting the environmental performance of the lifecycle. Mechanical stresses that may be applied to pipelines by landslides, flooding, thawing of permafrost, and erosion can enhance the occurrence of failures in sensitive environmental regions. The solution to these risks is both geohazard monitoring, design adaptation, and operational measures to minimize exposure to the high-risk conditions. The mitigation measures, however, should be well balanced against their own environmental footprint, as over-armoring or overconstruction intervention may also be disruptive to the ecosystem.

It is thus necessary to consider lifecycle environmental issues in engineering decisions to achieve sustainable pipeline management. This integration necessitates the synergy of the engineers, environmental specialists, and operational managers such that the design of infrastructure, integrity planning, and monitoring of the environment have similar performance goals. Digital technologies contribute to this integration more and more through the connection of operational data to the environmental monitoring system, mapping sensitive ecological receptors, and monitoring the results of the restoration process in time[58,59].

All in all, life cycle stewardship focuses on the fact that it is not single operational occurrences that result in environmental outcomes, but the ultimate decision made in the entire infrastructure lifecycle. This means that the management has to rely on coordinated strategies that involve preventive integrity programs, sound detection systems, and long-term planning of the environment.

5. Conclusion and Future Perspectives

This review observed the changing trend of engineering efficiency and environmental stewardship on the oil and gas pipeline systems. Instead of considering these objectives as autonomous goals, the literature has become increasingly clear that these objectives are managed by the same group of design choices, operational practices, integrity management strategies, and monitoring technologies. As integrated infrastructures, where routing decisions are made, decisions concerning hydraulic system design, selection of materials, operational pressure, and monitoring architecture are all made at the same time, affecting system performance, reliability, and environmental risk. Therefore, environmental protection cannot be treated as a spill response to the environment or regulatory compliance and should be integrated into the engineering decision-making of the whole pipeline lifecycle.

Many recurrent lessons are learned from the reviewed literature. To begin with, the infrastructure design and optimization of its operations have a significant impact on the level of energy efficiency and exposure to the environment. The choice of pipeline diameter, distance between stations, pressure regimes, and routing has parameters that not just influence the hydraulic performance but also the stress distribution, corrosion susceptibility, and the consequences that might arise as a result of its failures. Optimized system design, hence saves on energy usage, besides enhancing reliability and minimizing environmental risk.

Second, integrity management is at the center of the operation, reliability, and environmental protection. Corrosion, cracking, and geohazard mechanisms are considered the major causes of pipeline failures. Proper integrity programs, such as preventive corrosion control, in-line inspection, and risk-based maintenance, enable the operator to control the degradation proactively to minimize the chance of leaks and allow pipelines to operate at or near optimum design conditions. In this respect, the role of integrity management as a safety measure is not confined to a safety measure but an efficient and sustainable infrastructure operation mechanism.

Third, the leak detection and monitoring systems are important levels of environmental protection in the case of failures, in spite of preventive actions. The development of computational pipeline monitoring, fiber-optic sensing, satellite surveillance, and aerial inspection technologies has increased the potential to detect anomalies in the systems of extensive infrastructure. Nevertheless, in the literature, it is always mentioned that there is no one technology that fully covers. The key to efficient environmental protection, then, lies in overlaying monitoring architectures that integrate several sensing strategies along with powerful response mechanisms in operation.

In spite of these improvements, there are still several issues that have not been solved. The performance measures employed to analyze the efficiency of pipelines, environmental risk, and effectiveness of monitoring are not consistent in all works, which cannot allow a direct comparison between the systems and technologies. Experimental results on detection thresholds and response times do not necessarily apply to operational conditions, where hydraulic variability, measurement error, and telemetry constraints may make leak detection complex. Besides, the use of new digital technologies, such as artificial intelligence, advanced analytics, and digital twin models, is still at the initial phase of implementation into pipeline management schemes.

Moving on, it can be proposed that in the future, the field of research should be aimed at creating interdependent solutions that incorporate engineering optimization, environmental monitoring, and digital infrastructure. The uniformity in performance measures would enhance inter-system analysis and benchmarking of both the productivity and environmental performance. Digital twin technologies have great opportunities in the connection between operational models and real-time monitoring data to allow predictive maintenance and fast anomaly detection. Simultaneously, climate-related geohazards (flooding, permafrost thaw, slope instability, etc.) will grow in significance, and new approaches, which combine environmental risk assessment with infrastructure design and operational planning, are needed.

Generally, the literature suggests a systems-based view of sustainable operation systems of pipelines through which engineering performance is integrated with environmental responsibility. With the combination of design optimization, preventive integrity management, innovative monitoring systems, and lifecycle environmental planning, it is possible to develop it to the next steps of efficiency and reduce ecological risk in the pipeline systems. It will then be necessary to continue interdisciplinary research and technological development in order to make sure that future pipeline infrastructure will satisfy not only the energy transportation requirements but also the changing environmental expectations.

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