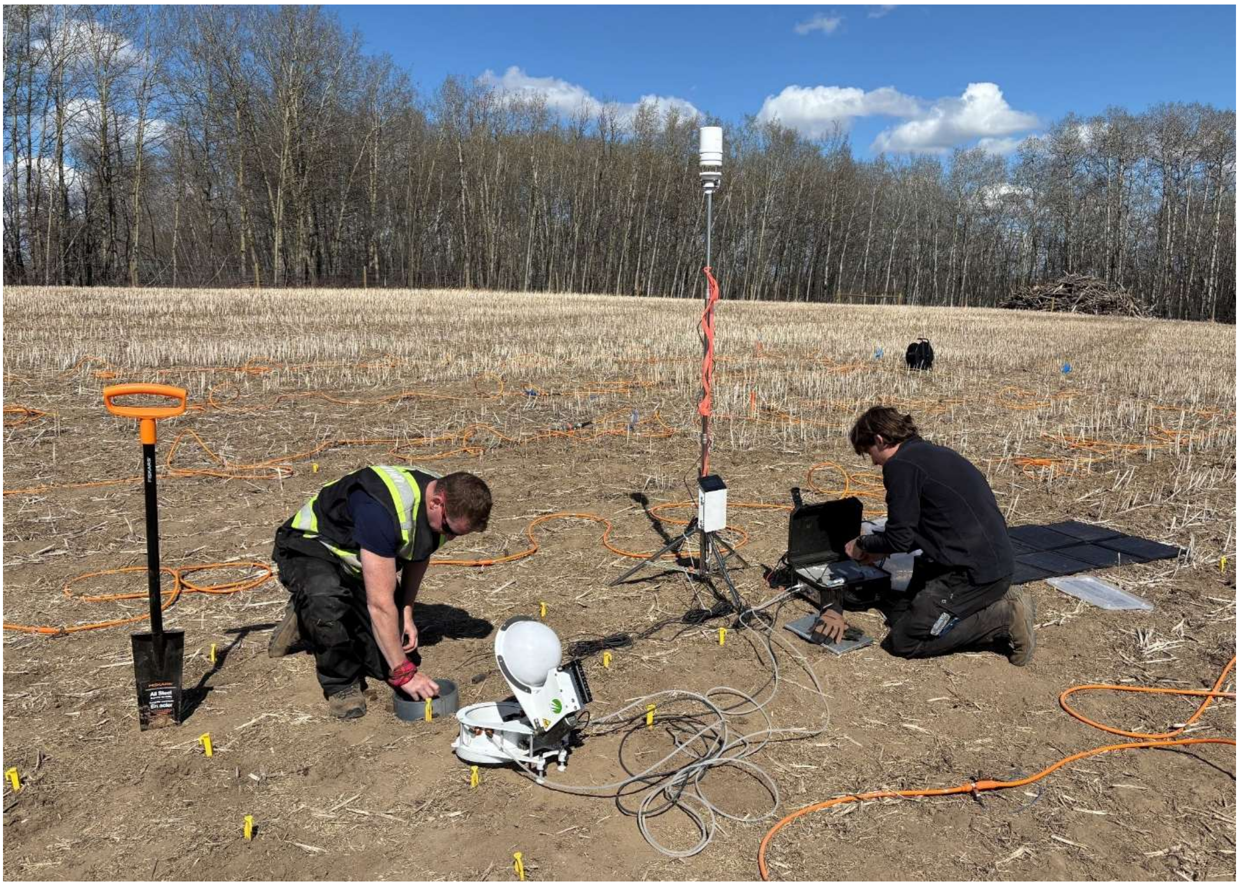
Research Project ES-Wells-2025-01 Technical Report:

# *Understanding Fugitive Methane Oxidation in Natural Soils of British Columbia Phase 3: Advanced Field Investigations, Wellsite J Risk Appraisal and Knowledge Dissemination*



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## Executive Summary

This report presents the findings and outcomes of Phase 3 of a BC OGRIS funded project examining methane leakage behaviour, natural attenuation, environmental significance, and management implications at legacy oil and gas wells in northeastern British Columbia. Building on earlier phases that identified Wellsite J as a persistent but comparatively low-magnitude leakage site with strong evidence of methane oxidation, Phase 3 focused on advancing process-level understanding, developing a site-specific management perspective, and disseminating project findings to scientific, technical, and regulatory audiences.

The focus of Phase 3 was an advanced field investigation programme at Wellsite J designed to improve process-level understanding of persistent low-level methane leakage and natural attenuation under field conditions. Two dedicated campaigns were completed in spring and fall 2025, generating an expanded multi-domain dataset that complements earlier summer observations. The work included $CH_4$–$CO_2$ surface flux measurements, continuous hotspot and soil-state monitoring, meteorological observations, geophysical surveys, shallow soil and subsurface characterization, and supporting geochemical and microbiological sampling. Together, these activities have made Wellsite J a well-characterised field example of low-level legacy-well leakage and natural attenuation.

The field campaigns showed that persistent methane leakage at Wellsite J produces a nested shallow footprint, comprising a compact methane efflux core, a broader $CO_2$ and geophysical response, and a wider geochemical alteration zone centred on the same persistent source. Continuous monitoring further showed that leakage expression is strongly influenced by soil moisture, rainfall, dry-down, temperature, and atmospheric forcing. These findings demonstrate that even modest leakage can be persistent, spatially structured, and strongly modified by shallow soil processes. They also show that snapshot measurements and methane-only interpretations can under-represent the full leakage system. The April/May and November campaigns also generated a rich seasonal-contrast dataset that will support further integration with prior summer observations, including future work on seasonal leakage expression, oxidation performance, and annualised interpretation.

Phase 3 also included a site-specific environmental risk appraisal and management perspective for Wellsite J. Using a proportionate source–pathway–receptor and weight-of-evidence approach, the appraisal concluded that Wellsite J is best understood as a persistent, naturally attenuated fugitive methane leakage system of low-to-moderate environmental significance under current evidence. Direct atmospheric $CH_4$ expression is compact and modest in greenhouse-gas terms, while $CO_2$, geophysical, geochemical, and microbiological indicators demonstrate a broader but localised shallow attenuation footprint. The recommended management posture is structured monitored management with targeted, condition-aware reassessment and defined escalation triggers, rather than passive no-action or immediate intrusive remediation by default.

Phase 3 further supported dissemination and knowledge transfer through open-access scientific publications, conference presentations, and bespoke technical presentations to professional and regulatory audiences, including the Well Integrity and Abandonment Society and the British Columbia Energy Regulator. These activities help ensure that the findings from Wellsite J inform wider understanding and practical discussion around legacy well leakage, monitoring, attenuation, and proportionate management. A recommended next step is to build on Phase 3 through a focused follow-on programme using Wellsite J as a field platform to test winter/freshet leakage behaviour, refine pathway and attenuation understanding, evaluate practical monitoring approaches, and assess transferability to other low-level leaking legacy wells in British Columbia.

## 1. Introduction and Context

Methane leakage from legacy oil and gas wells remains an important but incompletely resolved environmental issue in British Columbia and in other mature petroleum basins worldwide[1-6]. Where well integrity has degraded, legacy wells can act as vertical conduits for fugitive gas migration from depth, resulting in atmospheric emissions, shallow subsurface gas accumulation, and a range of associated environmental perturbations[3,7]. These issues matter in their own right from both greenhouse gas and environmental risk perspectives, but they also have broader significance in relation to subsurface resource management, regulatory oversight, and the long-term containment expectations now associated with emerging geoenergy applications such as carbon capture and storage[8,9].

Over the last several years, the BC OGRIS-supported research programme led by the author has progressively advanced understanding of fugitive gas release from integrity-compromised legacy wells in northeastern British Columbia. Earlier phases of work established that low-level leakage is not uncommon[10], that surface expression is often spatially heterogeneous and difficult to interpret, and that methane oxidation in shallow soils can substantially alter the near-surface manifestation of leakage[11]. In particular, earlier project work identified Wellsite J as a scientifically important case: a persistent but relatively low-magnitude methane leakage site exhibiting strong evidence of natural attenuation through near-surface oxidation, together with broader geochemical and gas-expression signatures extending beyond the immediate leak point. These findings highlighted both the environmental importance and the scientific value of the site.

This background created a clear rationale for Phase 3. Although previous work had shown that methane oxidation at Wellsite J was substantial and likely environmentally beneficial in reducing direct atmospheric methane release, important questions remained around how the system behaved under different field and hydrometeorological conditions, how spatial and temporal leakage expression could be integrated across observational domains, and how the broader environmental significance and management implications of low-level, attenuated leakage could be judged in a structured way. At the same time, the site was continuing to yield observations of unusual richness and consistency, suggesting that it could serve not merely as another leaking well, but as an archetype for understanding a wider class of integrity-compromised, low-leakage legacy wells.

Phase 3 was therefore conceived as a more advanced and focused investigation. Its central purpose was not to confirm that leakage occurs at Wellsite J, nor merely to add another increment of field data, but to move toward a more process-based understanding of how persistent low-level methane leakage is expressed, modified, and potentially attenuated in natural soil systems. This required a step change in observational depth, temporal resolution, and integration. In response, the project centred on a new programme of advanced field investigations at Wellsite J, including spring and fall campaigns that extended previous summer-biased observations and generated a broader, multi-domain dataset spanning fluxes, soil-state response, geophysical structure, geochemistry, and microbiology.

The project also recognised that scientific characterisation alone is not enough. A site such as Wellsite J raises broader questions around environmental significance, appropriate management posture, and how natural attenuation should be understood in practical terms. A low-leakage well that exhibits persistent but strongly attenuated methane loss may occupy a different management space from a high-flux, high-impact site, yet such cases are often difficult to contextualise within existing regulatory and operational frameworks. Phase 3 therefore also includes a site-specific appraisal of environmental risk and management perspective, alongside a knowledge dissemination component intended to support wider understanding of these issues in British Columbia.

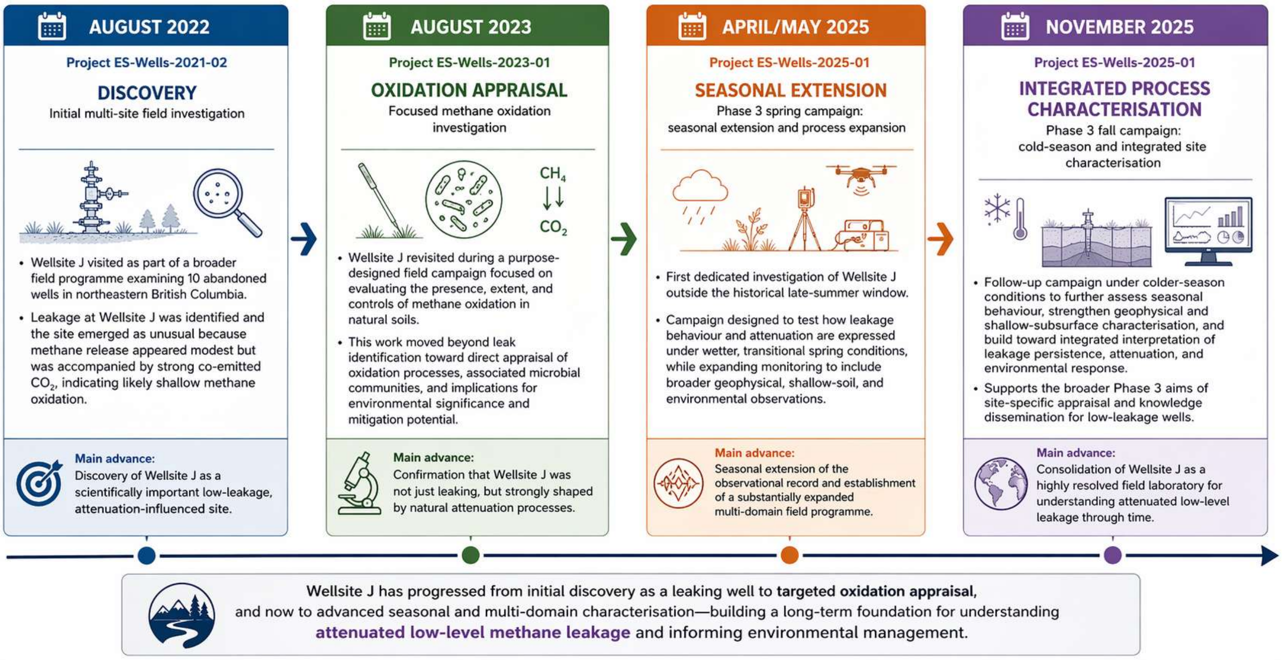


**Figure 1:** Evolution of field investigations at Wellsite J across successive BC OGRIS projects. The site progressed from initial discovery as a leaking well during a broader 10-well survey in 2022 under ES-Wells-2021-02, to targeted investigation of methane oxidation processes in 2023 under ES-Wells-2023-01, and then to advanced multi-domain field characterisation under contrasting spring and fall field conditions during 2025 under the current Phase 3 project, ES-Wells-2025-01. This progression illustrates how Wellsite J developed from an important field observation into a long-term research and management analogue for attenuated low-level methane leakage.

More broadly, Phase 3 matters because it addresses a class of leakage problem that is likely under-recognised but highly relevant. Much attention understandably focuses on high-emitting wells and obvious integrity failures. However, low-level but persistent leakage, especially where modified by oxidation and other shallow subsurface processes, may be more challenging to detect, interpret, and manage. These systems may leave subtle but coherent environmental footprints that are not captured well by single-gas, snapshot, or purely wellhead-centred measurement approaches. Understanding such cases is therefore important not only for fugitive methane assessment, but also for the wider challenge of interpreting complex leakage signals in legacy-well and geoenergy settings.

Against this backdrop, Phase 3 has proven to be an important step forward. The work reported here shows that Wellsite J now provides a strong field basis for examining low-level legacy-well leakage, methane oxidation, shallow subsurface response, and the environmental interpretation of attenuated gas release. The following sections describe the structure of the project, the investigations completed, and the principal findings and implications arising from this latest phase of work.

## 2. Project Structure, Aims and Objectives

The project was structured around three work packages. WP1, the dominant component, comprised advanced field investigations at Wellsite J to improve understanding of methane leakage expression, methane oxidation, and associated shallow subsurface responses under contrasting field conditions. Spring and fall 2025 campaigns generated a substantially expanded multi-domain dataset, complementing earlier summer-focused observations and supporting interpretation of how leakage signals emerge, persist, and interact with shallow soil conditions through time. WP2 developed a site-specific environmental risk appraisal and management perspective for Wellsite J, framed around its role as a low-leakage but integrity-compromised well where substantial natural attenuation appears to occur. WP3 focused on dissemination and broader knowledge transfer through reporting, publication outputs, conference activity, and stakeholder-facing communication.

The three work packages were not equivalent in scale. The clear centre of gravity was the WP1 field investigation programme, reflecting both the scientific opportunity presented by Wellsite J and the value of generating a richer field-based understanding of low-level leakage under natural conditions. WP2 and WP3 were designed as supporting and integrating components around that core.

The overall aim of Phase 3 was to advance understanding of how persistent, low-level methane leakage from an integrity-compromised legacy well behaves in natural soils, how it is modified by shallow biophysical and biogeochemical processes, and how such a site can be interpreted in environmental and management terms. This aim was addressed through three linked objectives.

First, the project sought to characterise the expression and attenuation of persistent methane leakage at Wellsite J under contrasting field and soil-state conditions. This included extending the evidence base beyond earlier summer-focused observations and examining how methane leakage, methane oxidation, and associated shallow subsurface responses vary across time, space, and changing environmental conditions. This was intended to support interpretation of Wellsite J as a persistent and structured leakage environment rather than a set of isolated or snapshot-based anomalies.

Second, the project aimed to place Wellsite J in a more structured environmental and management context. A central question was how a low-leakage site with persistent gas loss but strong apparent attenuation should be interpreted from a practical standpoint, including its environmental significance, management implications, and relevance as an archetype within the British Columbia legacy well population.

Third, the project aimed to extend the value of the work beyond the immediate site and dataset through final reporting, peer-reviewed publication outputs, conference dissemination, and communication with technical, regulatory, and stakeholder audiences.

Together, this structure gave Phase 3 a clear and coherent logic. Wellsite J was used as a high-value field setting for understanding persistent but comparatively low-magnitude methane leakage that is strongly modified by near-surface attenuation processes. The project structure therefore linked intensive field characterisation, environmental interpretation, and knowledge transfer into a single integrated programme. The following sections describe how the project was implemented, the principal findings now available, and the additional analyses that continue to build from the dataset generated.

# 3. WP1: Advanced Field Investigations

## 3.1. Rationale for focusing on Wellsite J

Wellsite J was selected as the central focus of WP1 because earlier OGRIS-supported work had shown it to be an unusually informative legacy well leakage site. It combined persistent methane leakage, comparatively low surface emissions, strong evidence of near-surface methane oxidation, and indications that leakage expression extended beyond a simple wellhead-centred methane anomaly. This made it a valuable field setting for examining how leakage from an integrity-compromised well is expressed, attenuated, and recorded in shallow environmental systems.

The site first emerged as significant during earlier regional investigations of fugitive gas release from legacy wells in northeastern British Columbia, where it was identified as one of a limited number of wells exhibiting clear evidence of methane leakage[10]. Subsequent focused work showed that its surface expression was spatially heterogeneous and strongly modified by methane oxidation in shallow soils[11]. Wellsite J therefore could not be interpreted adequately as a simple point-source methane emission feature. Instead, it provided a setting in which gas migration, microbial oxidation, soil conditions, geophysical response, and surface emissions could be examined together.

**Figure 2:** Wellsite J field setting during the April 2025 Phase 3 campaign. The site is located in an active agricultural field in northeastern British Columbia and is characterised by a buried, decommissioned legacy well with no obvious surface infrastructure expression.

A further reason for focusing on Wellsite J was that it occupied a useful middle ground between obvious high-risk leakage and negligible background variability. Leakage was demonstrably persistent, but not extreme in absolute magnitude, while natural attenuation appeared to be strongly active. This made the site valuable both scientifically, as a natural field laboratory for high-resolution study of shallow leakage behaviour, and practically, as a case for considering how persistent but attenuated leakage should be interpreted and managed.

For these reasons, Phase 3 was intentionally centred on Wellsite J rather than expanded outward to a larger number of wells. The objective was to build a deeper, more integrated understanding of the site that had already shown the greatest capacity to reveal how low-level legacy-well leakage is expressed across multiple observational domains.

### 3.2. Phase 3 field campaigns and dataset generated

A central component of Phase 3 was the completion of two dedicated field campaigns at Wellsite J during 2025. These campaigns were designed to extend the observational basis of the project beyond earlier summer-focused investigations and to generate a broader, multi-domain dataset for interpreting persistent low-level methane leakage, natural attenuation, and shallow environmental response. Earlier OGRIS-supported work had already provided strong evidence of persistent methane leakage and substantial near-surface methane oxidation, but further field evidence was needed to strengthen process-level understanding of how leakage expression varies across field conditions and observational domains.

Field investigations were undertaken during a spring campaign in April/May 2025 and a fall campaign in November 2025. These were conceived not as isolated site visits, but as complementary parts of an integrated field programme. Together, they expanded the evidence base across contrasting hydrometeorological conditions and generated datasets spanning surface gas fluxes, continuous hotspot and soil-state monitoring, atmospheric forcing, shallow soil and subsurface characterisation, geophysical imaging, geochemical observations, and supporting microbiological sampling. This field programme was a major deliverable of Phase 3 and forms the empirical basis for the principal scientific outputs arising from the project.

The spring campaign represented the first dedicated investigation of the site outside the historical August survey window and provided an important extension of the observational record under wetter, transitional conditions. It included surface flux investigations, continuous monitoring focused on the leakage hotspot, and a substantial geophysical programme centred on the site. Electrical resistivity tomography surveys, electromagnetic measurements, shallow temperature profiling, and targeted soil sampling were completed to characterise the shallow subsurface structure and environmental context of leakage expression.

The fall campaign extended this programme under colder field conditions through repeat and time-lapse geophysical imaging, expanded electromagnetic mapping, auger-based shallow subsurface sampling and temperature profiling, topographic survey work, and additional contextual measurements at Wellsite J and comparison/background locations. Together, the two campaigns moved the project beyond a summer-only or flux-only perspective and established a stronger observational framework for ongoing interpretation of spatial, seasonal, and cross-domain patterns.

**Figure 3:** Fieldwork at Wellsite J during the April/May (left) and November (right) 2025 Phase 3 campaigns. The images show contrasting field conditions during the two dedicated campaigns, including flux monitoring and shallow soil sampling around the leakage hotspot. Together, these campaigns extended the observational record beyond previous summer-focused work and generated the multi-domain dataset used to support Phase 3 interpretation.

The purpose of summarising the dataset here is not to reproduce the full campaign metadata, but to show the breadth and scientific logic of the Phase 3 field programme. The campaign design intentionally combined methods sensitive to different aspects of leakage expression, including direct gas flux, shallow-soil physical state, geophysical structure, and supporting geochemical and microbiological indicators. Table 1 summarises the principal datasets generated during Phase 3, together with the scientific role each plays in interpreting persistent low-level methane leakage at Wellsite J.

**Table 1. Principal datasets generated during Phase 3 field investigations at Wellsite J**.

| Measurement domain / method | Instrument / approach | Spring 2025 | Fall 2025 | Scientific relevance / expected leakage-related insight | Contribution to Phase 3 |
|---|---|---|---|---|---|
| **Surface gas flux mapping** | $CH_4$–$CO_2$ efflux surveys using chamber-based surface measurements | ✓ | ✓ | Surface flux mapping defines where methane and carbon dioxide are being emitted, how concentrated or diffuse those signals are, and how gas expression changes across the site. At leaking wells, methane commonly defines the narrowest source-centred footprint, while carbon dioxide may extend more broadly where oxidation is active. | Characterised the magnitude and geometry of surface gas expression at Wellsite J, provided the basis for evaluating persistence across contrasting field conditions, and underpinned later interpretation of hotspot structure and dual-gas behaviour. |
| **Continuous hotspot flux monitoring** | Repeated/continuous $CH_4$–$CO_2$ measurements at the leakage centre | ✓ | ✓ | Continuous monitoring captures short-term temporal variability that cannot be resolved by snapshot surveys. This is important because leakage expression may respond strongly to rainfall, soil moisture, | Enabled analysis of temporal dynamics, environmental forcing, and episodic departures from background leakage behaviour. |

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| | | | | temperature, and transient source behaviour. | |
| **Soil-state monitoring** | TEROS-12 soil sensors measuring volumetric water content, bulk electrical conductivity, and soil temperature, paired with local weather monitoring | ✓ | ✓ | Leakage can alter shallow soil physical state by changing gas-filled porosity, water retention, solute concentration, and heat transfer. Continuous paired measurements allow leakage-driven soil divergence to be separated from shared atmospheric forcing. | Provided the basis for resolving leakage-driven soil-state divergence, hydrological reset–recovery behaviour, and the emergence of a leakage-influenced shallow-soil regime. |
| **Meteorological forcing** | ATMOS weather station and supporting atmospheric observations | ✓ | ✓ | Local weather conditions regulate near-surface gas transport, soil wetting and drying, and thermal behaviour. Without these data, temporal changes in leakage expression cannot be interpreted robustly. | Provided the environmental context required to explain variability in gas fluxes and soil-state response through time. |
| **2D electrical resistivity tomography** | ERT dipole–dipole survey lines, including orthogonal and diagonal profiles | ✓ | ✓ | Resistivity surveys image shallow subsurface electrical structure. Leakage-related gas migration, moisture redistribution, and geochemical alteration can all perturb resistivity, making ERT a useful method for detecting structured shallow anomalies around persistent leakage zones. | Characterised the spatial structure of shallow subsurface perturbation around Wellsite J and provided a basis for comparing resistivity-centred anomalies across contrasting field conditions. |
| **3D resistivity / induced polarisation imaging** | 3D ERT/IP surveys with multiple electrode spacings and configurations | ✓ | ✓ | 3D imaging provides a more complete representation of shallow heterogeneity around the leakage centre than individual 2D lines alone. Induced polarisation may also help identify subtle changes in material or fluid properties associated with leakage and its biogeochemical effects. | Added higher-resolution imaging of the leakage-centred shallow subsurface and strengthened the multi-domain site characterisation achieved in Phase 3. |
| **Time-lapse resistivity monitoring** | Repeated 2D ERT survey over multiple days (Wenner array) | — | ✓ | Time-lapse resistivity helps assess whether shallow subsurface electrical structure is stable or changes over short timescales under changing field conditions. This is especially relevant where leakage interacts with variable moisture conditions. | Added an explicitly temporal geophysical component to the Phase 3 dataset and extended interpretation beyond static imaging. |
| **Electromagnetic conductivity mapping** | EM38-MK4 and EM31 surveys | ✓ | ✓ | Electromagnetic methods allow rapid mapping of bulk near-surface conductivity across wider areas than ERT. Leakage-related gas migration, oxidation, and associated changes in moisture and soil chemistry may generate broader conductivity patterns that complement flux and ERT observations. | Helped define the lateral extent and coherence of broader shallow conductivity structure around Wellsite J and provided wider-area geophysical context. |

| | | | | | |
|---|---|---|---|---|---|
| **Shallow soil sampling** | Discrete soil samples for physical and supporting laboratory analysis | ✓ | ✓ | Soil properties influence both gas migration and attenuation. Grain size, texture, and related physical characteristics help explain why leakage expression differs spatially and why soils respond differently under wetting and drying. | Supported interpretation of site heterogeneity and shallow material controls on leakage expression. |
| **Auger-based subsurface sampling and profiling** | Auger holes with shallow sample recovery and temperature profiling | Limited | ✓ | Vertical sampling and profiling help characterise shallow stratigraphy, thermal gradients, and material transitions that may influence gas migration, water movement, and near-surface attenuation processes. | Extended site characterisation below the immediate surface layer and improved understanding of vertical shallow-subsurface structure. |
| **Geochemical observations** | Soil and related geochemical measurements from targeted sampling | ✓ | ✓ | Persistent leakage and methane oxidation can alter shallow soil chemistry through carbonate dissolution/precipitation, ionic redistribution, and redox-related processes. These effects may produce broader and longer-lived signatures than instantaneous gas flux. | Provided evidence of longer-memory geochemical perturbation associated with persistent leakage and strengthened the integrated interpretation of site behaviour. |
| **Microbiological sampling** | Targeted shallow soil microbiological sampling | ✓ | ✓ | Microbial communities are directly relevant to methane oxidation and therefore to the attenuation of leakage before atmospheric release. Their composition and activity can help explain why a site exhibits strong oxidation capacity. | Added a biological process dimension to the project and supports emerging interpretation of attenuation mechanisms at Wellsite J. |
| **Thermal and hydrological context measurements** | Creek temperature / EC profiling and related contextual measurements | ✓ | ✓ | Local hydrological and thermal context can influence shallow environmental conditions around the site and help explain off-centre or broader environmental responses. | Provided supporting environmental context for interpreting leakage behaviour and shallow site processes. |
| **Site characterization and topographic survey** | Slope survey and related spatial control measurements | Limited | ✓ | Topography influences runoff, water redistribution, and the spatial organisation of shallow environmental conditions, all of which may affect leakage expression and interpretation. | Supported spatial analysis of the site and created a stronger basis for future conceptual and numerical modelling. |

Not all elements of this dataset are interpreted in equal depth within the present report. The purpose here is partly to document the scope of work completed and the evidence base generated through Phase 3, rather than to exhaustively analyse every dataset acquired. Some components, particularly those associated with the principal accepted, in-review, or near-submission publication outputs, are discussed in greater detail in later sections. Other datasets, including parts of the geophysical and microbiological work, remain under active analysis and will be developed more fully through subsequent outputs. Their acquisition nevertheless represents an important project outcome and increases the long-term value of Wellsite J as a field research site.

Together, the Phase 3 campaigns generated a dataset of substantially greater breadth and depth than had previously been available for Wellsite J. Importantly, this was not only a matter of collecting more data, but of establishing a stronger observational basis for understanding how leakage is expressed through time, how it is modified by shallow environmental processes, and how multiple lines of evidence can be integrated around a persistent but low-level leakage system. The resulting dataset now supports analyses spanning flux behaviour, shallow-soil state, geophysical structure, geochemical alteration, microbiological response, and environmental context, and has already underpinned several major scientific outputs arising from the project.

### 3.3. Major scientific findings to date

The principal findings arising from Phase 3 are being developed through a series of peer-reviewed scientific outputs, reflecting both the quality of the dataset generated and the significance of the results. At the time of writing, one major paper arising from the project has been published (open access), a second is under revision following peer review, and a third is in advanced manuscript preparation, with additional outputs anticipated as wider seasonal, geophysical, microbiological, and integrative datasets continue to be analysed. This publication trajectory is an important indicator of the scientific value delivered by Phase 3.

The purpose of this section is to provide a concise synthesis of the main findings that have emerged to date and to explain their relevance to the Phase 3 objectives. The emphasis is on the higher-level scientific advances and why they matter, rather than on full methodological or analytical detail.

Together, the findings show that Wellsite J is better understood as a persistent, structured, and dynamically expressed shallow environmental system than as a leaking well with isolated anomalies. Earlier OGRIS work had already established that methane leakage occurs at the site and that near-surface oxidation is important. Phase 3 has extended this substantially by showing that sustained low-level leakage produces a coherent multi-domain footprint, that this footprint is expressed differently across observational domains and timescales, and that the surface signal is strongly conditioned by shallow environmental processes. The main findings from phase 3 are now summarized.

**Persistent, nested, multi-scale leakage footprint:** A first major finding is that leakage at Wellsite J leaves a persistent and spatially organised footprint that extends beyond the immediate methane emission hotspot. The published GRL study demonstrates that repeated surface flux measurements, geophysical observations, and soil geochemical data define coherent leakage-related anomalies centred on the same physical source location, but expressed over markedly different spatial scales[12]. The site therefore does not exhibit a single leakage signal, but a nested structure in which methane efflux is highly localised, geophysical response is broader, and geochemical alteration broader still.

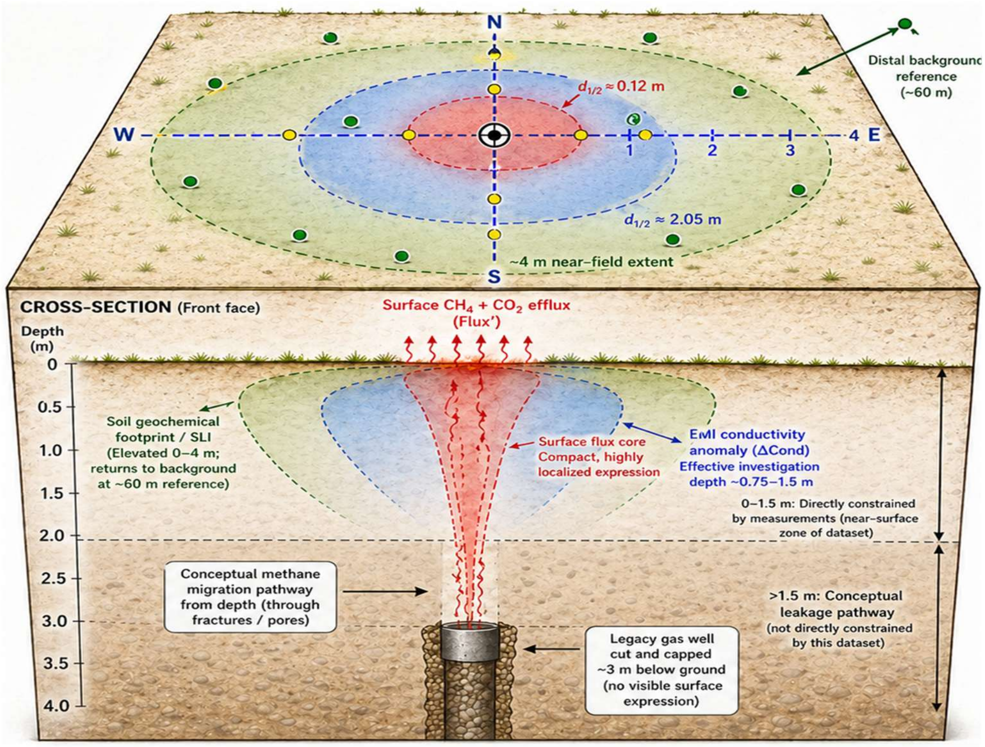



**Figure 4:** Conceptual model of Wellsite J leakage showing the nested, multi-scale shallow footprint observed during the April 2025 field campaign. Persistent fugitive gas migration from the buried legacy well generates a compact and spatially variable surface $CH_4$ + $CO_2$ efflux core centred on the well location. This direct flux expression is highly localised, with a characteristic half-distance of approximately ~0.1 m, but occurs within a broader co-centred geophysical anomaly identified by electromagnetic conductivity data, with a characteristic half-distance of approximately ~2 m. This, in turn, sits within a wider near-field soil geochemical alteration zone extending approximately ~4 m from the well and returning to background at the distal reference location approximately 60 m away. The figure illustrates that Wellsite J is not adequately represented as a simple point methane source: direct surface efflux is compact, while the shallow subsurface records a broader legacy of gas migration, methane oxidation, and associated geophysical–geochemical alteration.

This finding matters because it changes how low-level leakage should be understood. The compact methane surface-flux footprint confirms active, spatially anchored leakage, but the broader conductivity anomaly and geochemical soil halo show that the environmental imprint of leakage extends beyond the zone of strongest surface methane emission. Direct flux measurements remain critical, but they represent the shortest-memory diagnostic. Geophysical and geochemical indicators integrate leakage effects over longer timescales and provide a more stable basis for delineation and interpretation where emissions are weak, compact, or intermittently suppressed.

**Dual-gas behaviour, temporal variability, and the limits of snapshot interpretation:** A second major finding is that methane and carbon dioxide at Wellsite J exhibit contrasting but complementary patterns of surface expression. The Journal of Geophysical Research: Atmospheres study currently under review shows that methane emissions remain concentrated within a compact and persistent hotspot, whereas carbon dioxide defines a broader and more spatially extensive surface halo. This broader $CO_2$ expression is consistent with shallow oxidative redistribution of methane during upward transport through the vadose zone. The site therefore expresses leakage as a coupled $CH_4$–$CO_2$ system shaped by attenuation, rather than as methane loss alone.

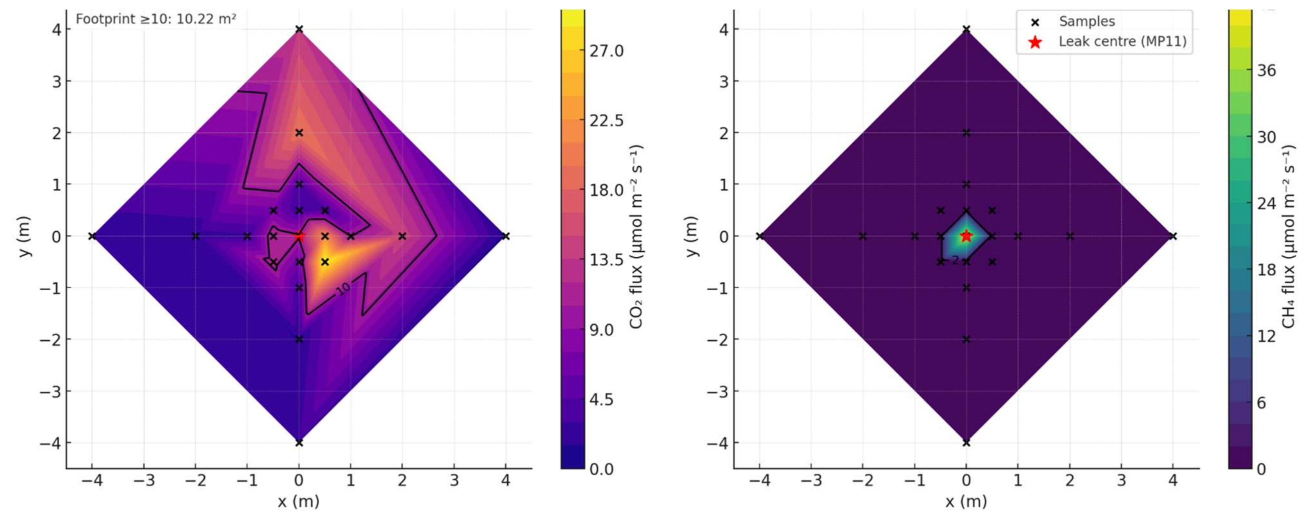



**Figure 5:** Spatial distribution of $CO_2$ and $CH_4$ surface fluxes during Survey 1 at Wellsite J. Fluxes of (a) $CO_2$ and (b) $CH_4$ were interpolated using Natural Neighbour interpolation and clipped to the convex hull of the monitoring network. Sample locations are shown as black crosses and the interpreted leakage centre (MP11) is marked by a red star. Negative flux values were clipped to zero for display. Fixed colour scales and contour thresholds highlight the contrast between gases: the $CO_2$ anomaly extends across approximately 10.2 m², whereas the $CH_4$ anomaly is confined to approximately 0.54 m² around the leakage centre. This pattern demonstrates that direct $CH_4$ efflux is sharply localised, while $CO_2$ expression is broader and more diffuse, consistent with near-surface methane oxidation and associated shallow soil respiration/redistribution processes.

The same analysis shows that leakage expression is temporally dynamic. Baseline methane flux is strongly modulated by soil moisture, matric state, temperature, atmospheric pressure, and related environmental controls, while episodic high-flux events are not fully explained by surface drivers and likely reflect transient variation in subsurface release behaviour. The surface signal is therefore neither random nor purely source-controlled, but the product of a coupled source–soil–atmosphere system.

This has important implications for monitoring. Flux magnitude at any one moment is not a sufficient indicator of overall leakage significance. A low measured methane flux may reflect low source delivery, but it may also reflect strong near-surface attenuation or temporary environmental suppression. Methane-only surveys may under-interpret leakage where oxidation is active, and isolated monitoring events can be misleading if they occur during periods when the leakage signal is masked by rainfall, elevated soil moisture, or other transient controls. These results reinforce the need for time-aware, multi-species, and environmentally contextualised monitoring approaches.

Phase 3 has therefore moved the site beyond a late-summer snapshot understanding. The available findings show that Wellsite J is persistent, but its surface expression is dynamic and condition-dependent. Full integration of spring, fall, and prior summer observations remains an ongoing follow-on analysis, but the current results already demonstrate that robust interpretation requires explicit consideration of both attenuation and environmental forcing.

**Shallow-soil response to persistent leakage:** A third major finding emerging from Phase 3 is that sustained methane leakage at Wellsite J may influence shallow-soil physical state through time. Continuous paired monitoring of soil water content, electrical conductivity, and temperature indicates that the leakage centre can remain differentiated from nearby reference soils under the same meteorological forcing. The leak-centre records show contrasts in moisture, electrical conductivity, and thermal behaviour that provide a basis for evaluating whether persistent gas migration and associated attenuation processes influence shallow-soil physical state.

Rainfall events provide useful natural perturbations for interpreting the paired records, because they allow leak-centre and reference soils to be compared during wetting, drainage, and dry-down periods. This creates a basis for evaluating how antecedent moisture and hydrological state influence the detectability and temporal expression of leakage-related signals. Detailed interpretation of these soil-state dynamics is ongoing and will be developed further in subsequent publication outputs.


**Figure 6.** Continuous soil-state monitoring at the Wellsite J leakage centre and distal reference location. Time series show volumetric water content, soil temperature, and bulk electrical conductivity measured at the leakage centre and at a nearby distal reference location approximately 2 m from the leakage centre, together with daily rainfall totals. The records illustrate the type of paired soil-state dataset generated during Phase 3 and show that leak-centre and distal soils can be compared directly under the same meteorological forcing. These data provide a basis for evaluating how shallow soil conditions, rainfall, and antecedent moisture influence the temporal expression of leakage-related signals. Detailed interpretation of the soil-state response is ongoing and will be developed further in subsequent publication outputs.

## Integrated significance of the Phase 3 findings

Overall, the findings of Phase 3 show that Wellsite J is now one of the best-characterised examples of persistent low-level methane leakage at a legacy petroleum well. More importantly, the site demonstrates that low-level leakage can be real, persistent, and environmentally structured even where direct methane emissions are modest and strongly attenuated before reaching the atmosphere. Such systems may be easy to underestimate if interpretation relies only on direct methane measurements or short-duration field snapshots.

These results are directly relevant to BC OGRIS and to stakeholders concerned with integrity-compromised wells in British Columbia. They suggest that low-leakage wells may require a more nuanced approach, particularly where natural attenuation is substantial and where environmental significance cannot be judged reliably from methane flux alone. The principal contribution of Phase 3 is therefore not the generation of more data, but the provision of a clearer and more defensible framework for interpreting low-level fugitive gas release at sites such as Wellsite J.

### 3.4. Additional datasets under analysis

While the principal findings outlined above already represent a substantial scientific advance from Phase 3, they do not exhaust the full value of the dataset generated at Wellsite J. A notable strength of the project is that it produced a broader and more diverse body of evidence than could reasonably be interpreted in full within a single technical report or immediate set of publication outputs. In addition to the analyses that have already progressed to published, in-review, or near-submission papers, further seasonal, geophysical, microbiological, and integrative datasets remain under active evaluation and are expected to yield additional insight as the work continues.

A specific example is the seasonal-contrast objective of Phase 3. The April/May and November 2025 campaigns successfully extended previous summer-focused observations into contrasting field conditions and generated the dataset needed to evaluate seasonal controls on leakage expression, methane oxidation, and shallow environmental response. Full integration of these spring/fall observations with prior summer data remains ongoing and is being treated as a dedicated follow-on synthesis, reflecting the scale and richness of the dataset rather than a limitation of field delivery. The present report therefore captures the key condition-aware findings available to date, while recognising that a more complete seasonal and annualised interpretation of leakage and oxidation behaviour will be developed through subsequent analysis and publication.

A further major component of this ongoing effort relates to the geophysical programme completed during the spring and fall 2025 campaigns. Phase 3 generated a much more extensive geophysical dataset than had previously been available for the site, including repeat 2D electrical resistivity imaging, higher-resolution 3D resistivity and induced polarisation surveys, time-lapse measurements, and broader electromagnetic mapping. These data have not yet been fully synthesised within the present report, but they are expected to further refine understanding of the shallow subsurface structure associated with persistent leakage at Wellsite J, including the geometry, persistence, and environmental context of geophysically expressed anomalies.

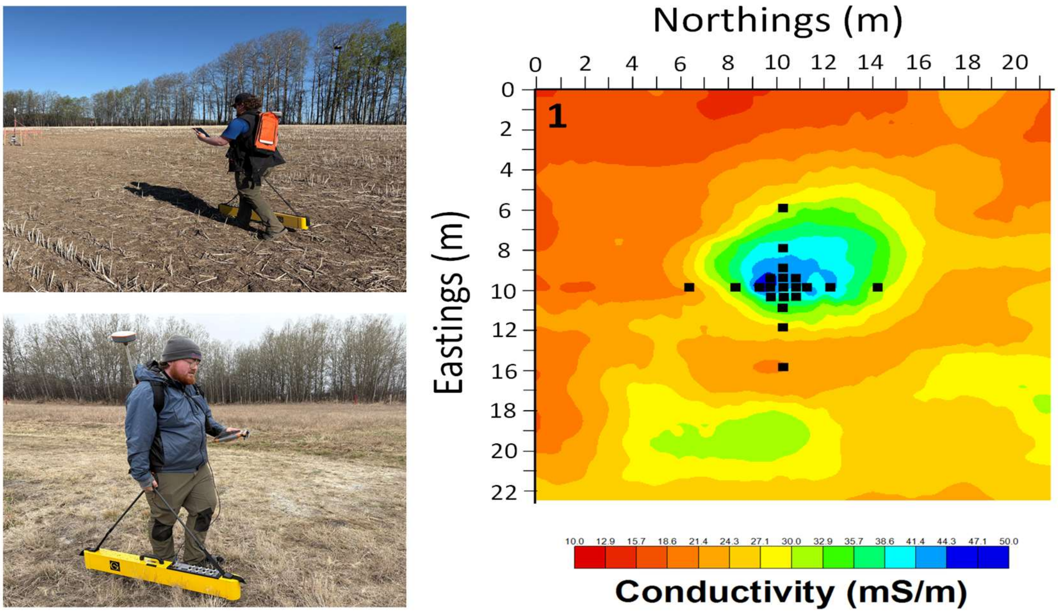



**Figure 7:** Electromagnetic induction survey at Wellsite J and associated shallow conductivity anomaly. Field photographs show electromagnetic induction measurements being collected across the agricultural field using a portable ground-conductivity instrument. The interpolated conductivity map shows a localised, co-centred electromagnetic anomaly around the inferred leakage centre, marked by the cluster of sampling points near the well location. The anomaly is expressed as elevated apparent electrical conductivity relative to surrounding background conditions and is spatially broader than the compact surface $CH_4$ efflux core. This pattern supports the interpretation that persistent fugitive gas migration and methane oxidation are associated with a measurable shallow subsurface alteration footprint, potentially reflecting coupled changes in pore gas, moisture, redox/geochemical conditions, and soil electrical properties within the near-field leakage zone.

Additional microbiological and biogeochemical datasets are also still being worked through. These are important because one of the central interpretive themes at Wellsite J is that methane oxidation is not incidental, but a major control on how leakage is expressed at the surface and in the shallow subsurface. While earlier and current project phases have already established strong indirect and direct evidence for substantial oxidation, the newer biological datasets offer the prospect of further constraining the microbial basis of this attenuation capacity and of clarifying how biological and physicochemical processes interact under changing field conditions. This is particularly relevant given the broader project objective of understanding not only whether attenuation occurs, but how and under what conditions it modifies environmental significance.

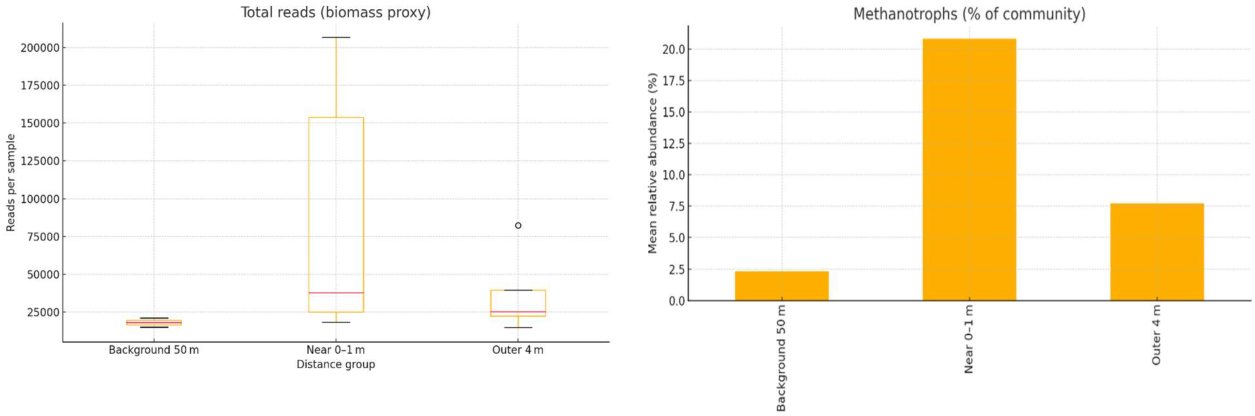



**Figure 8.** Microbiological response to persistent methane leakage at Wellsite J. (a) Total sequencing reads per sample, used here as a broad biomass/DNA-yield proxy, show elevated values in the near-field leakage zone compared with the distal background location, although variability is high and influenced by one particularly read-rich sample. (b) Mean relative abundance of methanotroph-associated taxa increases strongly toward the leakage centre, rising from approximately 2% of the community at the 50 m background location to >20% in the 0–1 m near-field zone, before declining at the outer 4 m location. This spatial pattern is consistent with methane availability structuring the shallow soil microbial community and supports the interpretation that biological methane oxidation is likely to be an important attenuation process within the leakage-affected near-field soils.

It is important to emphasise that the presence of ongoing analyses should not be interpreted as a weakness or incompleteness of Phase 3. On the contrary, it reflects the scale and quality of the dataset generated and the fact that the project has produced a richer scientific resource than could be fully harvested within the immediate reporting period. The current report therefore captures the principal findings that are already mature and directly relevant to the project objectives, while also documenting the existence of additional datasets that materially enhance the long-term value of the work.

It should be noted that some interpretation boundaries remain. Seasonal and annualised oxidation performance is not yet fully resolved, particularly under winter, frozen-ground and freshet conditions. Geophysical and geochemical anomalies are interpreted as leakage-associated based on their spatial coherence and co-location with the source, but they remain indirect indicators and should be considered alongside flux, soil-state, isotope and microbiological evidence. The findings are also site-specific until tested against selected comparator wells. These limitations do not weaken WP1 findings, but they define the appropriate scope for interpretation and future work.

### 3.5. Implications of WP1 findings

The Phase 3 findings at Wellsite J have implications beyond the characterisation of a single leaking well. They provide a clearer basis for understanding the environmental meaning of persistent low-level methane leakage, the role of natural attenuation in modifying that meaning, and the challenges this creates for detection, interpretation, and management. The key value of WP1 is what it suggests about a wider class of integrity-compromised legacy wells that may be environmentally relevant despite modest or spatially compact methane emissions.

A first implication is that low-level leakage should not be treated as environmentally trivial simply because direct methane emissions at the surface are modest. At Wellsite J, persistent leakage is associated with a broader shallow footprint than methane flux alone would imply, including geophysical, geochemical, and soil-process indicators extending beyond the immediate methane hotspot. At the same time, substantial methane oxidation appears to reduce the direct atmospheric methane burden. The environmental significance of the site lies in the interaction between persistent source activity and shallow attenuation, rather than in either methane flux magnitude or attenuation alone.

A second implication is that natural attenuation is central to leakage interpretation. At Wellsite J, methane oxidation helps explain why the surface methane signal is compact, why carbon dioxide expression is broader, and why the shallow subsurface records a larger environmental footprint than the direct methane hotspot. From a management perspective a well may be actively leaking while producing only modest methane emissions at the surface because a significant fraction of the gas is transformed during upward migration. Attenuation therefore reduces one component of environmental significance, but it does not remove the source or eliminate the need for interpretation and stewardship.

A third implication concerns monitoring design. The Phase 3 findings show that leakage expression is spatially structured and condition-dependent. Methane is concentrated in a narrow hotspot, while carbon dioxide, geophysical response, and geochemical alteration record broader or longer-memory aspects of the system. Soil-state observations add further context by showing how shallow environmental conditions may influence the timing and expression of leakage-related signals. This means that detection performance depends not only on what is measured, but also on when and how it is measured. Single-gas surveys, isolated site visits, or measurements made without reference to antecedent field conditions may under-represent the true leakage system.

These points are particularly relevant in a regulatory and operational context. Conventional methane-centred surveys may be effective for obvious high-flux cases, but they are less reliable for subtle, attenuated, or environmentally modulated leakage systems. The Wellsite J results indicate that persistent low-level leakage can still produce coherent and detectable environmental signatures, but these may require integrated interpretation across flux, geophysical, geochemical, soil-state, and microbiological evidence. Equally, where strong attenuation is demonstrable, there may be scope for a more proportionate management response than would be implied by leakage presence alone.

Overall, the implications of WP1 are both scientific and practical. Scientifically, Phase 3 has advanced understanding of how low-level methane leakage behaves in natural soils and how its expression is modified by attenuation and field conditions. Practically, it shows that environmental impact, risk, and detectability cannot be judged reliably from methane measurements alone. The central message is that persistent low-level leakage may be more structured and environmentally relevant than conventional interpretations assume, but also that its significance can be better contextualised where natural attenuation and receptor exposure are explicitly considered.

**Table 2:** Key implications of WP1 findings for leakage interpretation, monitoring, and management

| Phase 3 finding | What it means | Why it matters for management and regulation |
|---|---|---|
| **Leakage is persistent but low in direct methane magnitude** | Low measured methane flux does not mean the well is inactive or environmentally irrelevant. | Low-level leakage may still warrant attention where it is sustained through time. |
| **The leakage footprint is nested across flux, geophysical, and geochemical domains** | Different methods capture different parts of the leakage system and different timescales of response. | Methane flux alone may under-represent the full shallow environmental footprint. |
| **Methane and carbon dioxide show contrasting surface behaviour** | Shallow oxidation modifies how leakage appears at the surface. | Paired $CH_4$–$CO_2$ measurements are more informative than methane-only surveys where attenuation is active. |
| **Surface expression is affected by weather and soil conditions** | Leakage signals may be suppressed, amplified, or redistributed by field conditions. | Monitoring should account for timing, rainfall, soil moisture, and antecedent conditions. |
| **Soil-state records provide additional process context** | Paired soil sensors help evaluate how shallow soil conditions relate to leakage expression. | Soil-state monitoring may support interpretation, especially where flux signals are subtle or variable. |
| **Natural attenuation is a major control on environmental expression** | Source activity and atmospheric methane impact are not equivalent. | Risk interpretation should consider both leakage persistence and attenuation capacity. |
| **Wellsite J represents an attenuated but active leakage archetype** | Not all leaking wells are environmentally equivalent. | A proportionate, evidence-based management framework is appropriate for low-leakage attenuated wells. |

# 4. WP2: Site-Specific Environmental Risk Appraisal and Management Options for Wellsite J

## 4.1. Purpose and scope

WP2 translates the scientific evidence generated at Wellsite J into a concise site-specific environmental risk appraisal and management perspective. The purpose was not to undertake a full generic contaminated-land risk assessment or detailed remedial options appraisal, but to assess what the observed leakage behaviour means for environmental significance and proportionate management.

The full appraisal is provided in **Appendix A**. This summary presents the principal findings and recommended management position for inclusion in this main technical report.

Wellsite J is an important case because it does not present simply as a high-flux point methane source. The evidence indicates persistent fugitive methane leakage from an integrity-compromised legacy well, but with strong modification of the surface expression by shallow soil processes. Direct $CH_4$ expression is compact, $CO_2$ expression is broader, and multiple lines of evidence indicate substantial methane oxidation in the vadose zone. The site is therefore best understood as an attenuated but active leakage system: leakage is real and persistent, but natural attenuation materially modifies its magnitude, spatial expression, and environmental significance.

The appraisal outlined in detail in Appendix A used a proportionate source–pathway–receptor approach supported by a weight-of-evidence interpretation of the site-specific dataset. The central management question is: what level of environmental significance and management response is justified given the source behaviour, attenuation, spatial footprint, receptor context, and uncertainty.

## 4.2. Conceptual interpretation

The conceptual site model developed for WP2 interprets Wellsite J as a persistent, structured, dynamically expressed shallow leakage system. Fugitive $CH_4$ migrates upward from the buried legacy well through the shallow subsurface and vadose zone. During this upward migration, a substantial fraction of the $CH_4$ is oxidised microbially to $CO_2$ before reaching the atmosphere. This produces a nested shallow footprint: a compact $CH_4$ emission core, a broader $CO_2$/oxidation footprint, and a wider geophysical–geochemical–microbiological response in near-field soils.

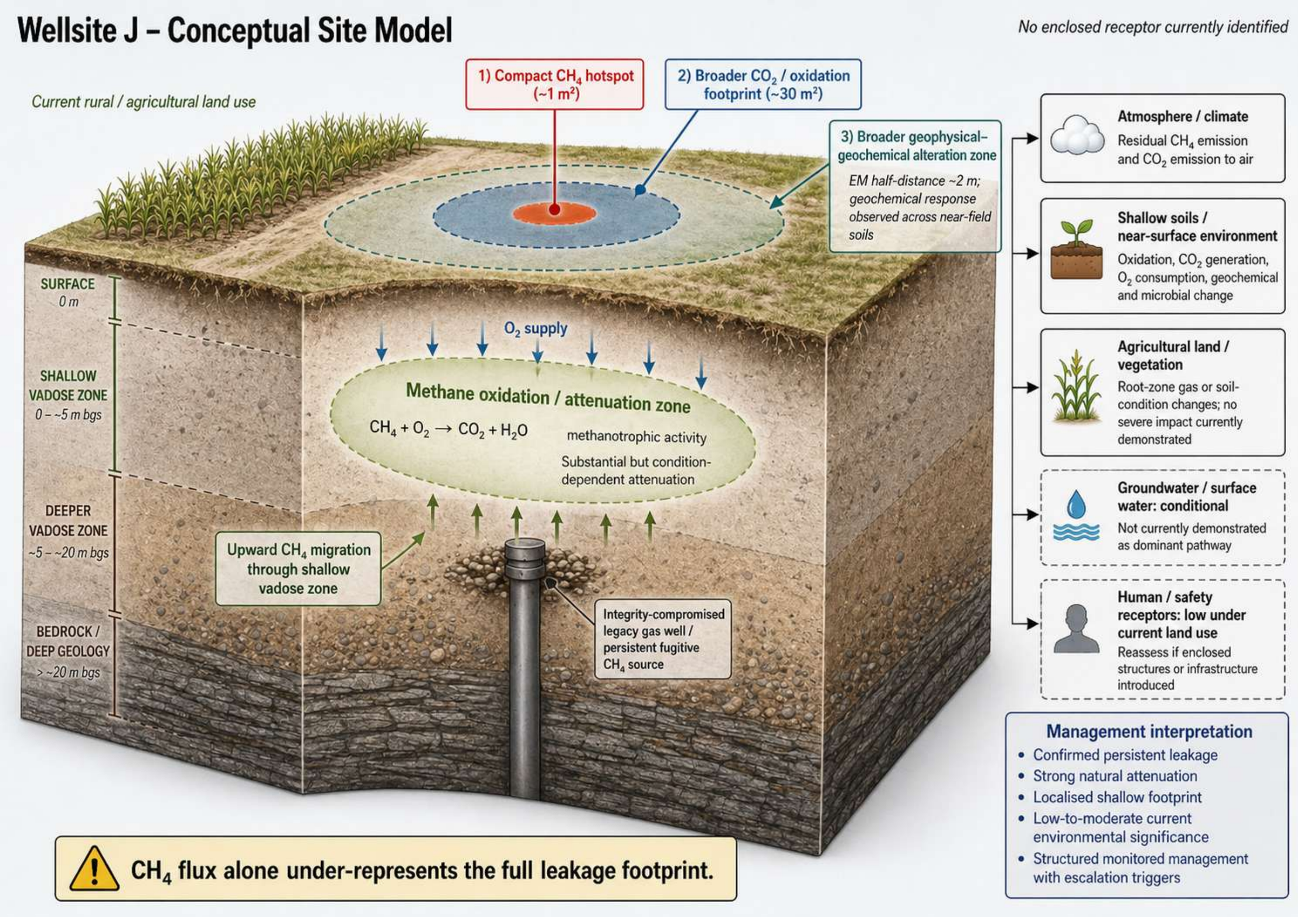



**Figure 9:** Conceptual site model for Wellsite J. Persistent fugitive $CH_4$ leakage from an integrity-compromised buried legacy well migrates upward through the shallow vadose zone, where substantial but condition-dependent methane oxidation attenuates atmospheric $CH_4$ release and generates a broader $CO_2$ and shallow alteration footprint. Current receptor linkages are strongest for atmosphere/climate and shallow soils, while groundwater, surface water, and human/safety receptors remain conditional under the present rural/agricultural land-use setting.

This conceptual model is important because $CH_4$ flux alone does not fully represent the leakage system. Low or compact $CH_4$ expression at the ground surface may reflect effective oxidation, not absence of leakage. Conversely, the broader $CO_2$, geophysical, geochemical, and microbiological signatures demonstrate that attenuation reduces atmospheric $CH_4$ expression while also generating a measurable shallow environmental footprint.

### 4.3. Key evidence relevant to environmental significance

The WP2 appraisal draws on repeated $CH_4$–$CO_2$ surface flux surveys, depth-profile measurements, stable isotope evidence, microbiological data, soil geochemistry, geophysical mapping, continuous hotspot monitoring, and paired soil-state and meteorological observations. Together, these data show that Wellsite J is a confirmed and persistent fugitive gas leakage site, but one where direct atmospheric expression is substantially moderated by shallow soil oxidation.

The most management-relevant findings are:

- Leakage is confirmed and persistent, with repeated $CH_4$ and $CO_2$ anomalies centred on the wellhead area across multiple investigations.

- Direct $CH_4$ expression is spatially compact, with 2025 monitoring indicating a persistent $CH_4$ hotspot of approximately 1 m².
- $CO_2$ expression is broader, with a footprint of approximately 30 m², consistent with shallow methane oxidation and redistribution.
- Depth-profile data show much higher $CH_4$ flux at 1 m depth than at the surface, supporting substantial vadose-zone attenuation before atmospheric release.
- Methane oxidation is a major control on site expression, with high summer-condition oxidation estimates and strong microbiological evidence for active methanotrophy.
- Attenuation is condition-dependent and likely varies seasonally; therefore, summer oxidation performance should not be assumed to represent all annual conditions.
- The broader shallow footprint is measurable through geophysical, geochemical, and microbiological indicators, but appears localised to the near-field area around the well.
- Current receptor exposure appears limited by the rural/agricultural setting, with no present evidence of acute human safety risk, groundwater impact, surface-water impact, or severe vegetation/crop impact.

These findings support a balanced interpretation. Wellsite J should not be treated as environmentally negligible, because leakage is persistent and the shallow footprint is measurable. However, the current evidence also does not support classification as an acute, severe, or widespread receptor-impact site.

**Table 3: Well site J summary risk appraisal and management implications**

| Appraisal element | Main interpretation | Management implication |
|---|---|---|
| **Source status** | Confirmed persistent fugitive gas leakage from a buried legacy well. | Do not treat as background or "no issue". A documented management position is required. |
| **Direct $CH_4$ expression** | Real and persistent, but spatially compact and modest in total greenhouse-gas terms under observed conditions. | Continue targeted hotspot monitoring; avoid reliance on single snapshot measurements. |
| **$CO_2$ / oxidation expression** | $CO_2$ footprint is broader than $CH_4$ and is interpreted as a key indicator of shallow methane transformation. | Measure $CH_4$ and $CO_2$ together; do not use $CH_4$ alone as the basis for appraisal. |
| **Natural attenuation** | Methane oxidation materially reduces atmospheric $CH_4$ expression, especially under favourable conditions. | Treat attenuation as a beneficial but condition-dependent management-relevant process, not as source removal. |
| **Shallow soil footprint** | Geophysical, geochemical, and microbiological indicators demonstrate measurable near-field alteration. | Track footprint stability where future monitoring is undertaken. |
| **Receptor setting** | Strongest linkages are atmosphere/climate and shallow soils; groundwater, surface water, vegetation, and safety receptors remain conditional under current evidence. | Retain receptor review triggers, particularly if land use, drainage, infrastructure, or groundwater evidence changes. |

| | | |
|---|---|---|
| **Overall significance** | Active, persistent, attenuated leakage system with modest atmospheric burden and localised shallow footprint. | Low-to-moderate environmental significance under current evidence. |
| **Preferred management response** | Confirmed but constrained / attenuated leakage with targeted uncertainty around seasonal attenuation and long-term stability. | Structured monitored management; targeted investigation, mitigation, or remediation only if escalation triggers are met. |

### 4.4. Environmental significance

The overall environmental significance of Wellsite J is assessed as low to moderate under the current evidence base. This classification reflects three linked findings. First, fugitive gas leakage is confirmed and persistent. Second, direct atmospheric $CH_4$ expression is spatially compact and modest in total greenhouse-gas terms under observed conditions. Third, the leakage has generated a measurable shallow footprint through methane oxidation, $CO_2$ generation, geophysical response, geochemical alteration, and microbial community change.

The strongest complete source–pathway–receptor linkages are to the atmosphere and shallow soils. Atmospheric release is relevant because $CH_4$ does reach the surface, but natural oxidation substantially reduces the direct $CH_4$ burden relative to an equivalent unattenuated leakage source. The shallow soil linkage is also relevant because oxidation and associated gas transformation generate a broader local footprint than would be inferred from $CH_4$ flux alone.

Other receptors are currently less strongly expressed. Agricultural land and vegetation are plausible receptors, but severe crop or vegetation impact has not been demonstrated. Groundwater and surface water should be retained as conditional receptors, but they are not presently demonstrated as dominant or complete pathways. Human health and safety receptors also appear limited under the current open rural/agricultural land-use setting, with no evidence of enclosed-space accumulation or acute explosive hazard near the hotspot. These conclusions should be revisited if site conditions, land use, drainage, infrastructure, or monitoring evidence changes.

### 4.5. Suggested management position

The full WP2 appraisal classifies Wellsite J, using a reduced-order site-specific decision framework, as a confirmed but constrained/attenuated leakage site. This is not intended as a formal regulatory class, but as an appraisal category for this site-specific management context. It reflects a site where leakage is confirmed and persistent, but emissions are low to moderate, the footprint is localised, attenuation is demonstrated, and receptor exposure is limited under current conditions.

The most proportionate management response is therefore structured monitored management, supported by targeted, condition-aware reassessment and defined escalation triggers. This position is not equivalent to “do nothing.” It recognises that the well remains an active source and that the shallow soils are functioning as a reactive attenuation zone. The management objective is to verify that the current risk posture remains valid.

A proportionate monitoring approach does not need to replicate the full Phase 3 scientific programme. Instead, it should focus on a small number of indicators linked directly to source behaviour, attenuation performance, footprint stability, and receptor exposure. At minimum, this should include repeat $CH_4$ and $CO_2$ flux measurements at the known hotspot and immediate near-field area, basic soil-state observations to contextualise attenuation potential, and a visual receptor check for vegetation stress, drainage changes, land-use change, or new infrastructure.

Periodic monitoring outside peak summer oxidation conditions would be particularly valuable, because winter or shoulder-season conditions may provide a more conservative test of attenuation performance. The purpose would not be to generate a new intensive research dataset, but to test whether the core assumptions of the appraisal remain valid when biological oxidation may be less favourable.

Escalation to targeted investigation, mitigation, or remediation should be considered if future monitoring demonstrates:

- sustained increase in $CH_4$ flux magnitude or frequency of high-flux events;
- expansion of the $CH_4$ hotspot beyond the established compact footprint;
- weakening of the $CO_2$/oxidation signature or evidence that $CH_4$ is increasingly bypassing the oxidation zone;
- expansion of the broader $CO_2$, geophysical, or geochemical footprint;
- evidence of persistent vegetation stress or soil-function impairment;
- groundwater or surface-water linkage attributable to the leakage system;
- introduction of enclosed structures, utilities, confined spaces, or other human/safety receptors near the leakage zone;
- evidence that the current low-to-moderate significance classification is no longer valid.

Under current evidence, immediate intrusive remediation, re-entry, or re-abandonment is not recommended as the default response. Such intervention should remain available as an escalation option if emissions increase, attenuation weakens, the footprint expands, or receptor exposure becomes more material. In the absence of those triggers, intrusive remediation would represent a higher level of intervention than is currently supported by the evidence.

### 4.6. Summary conclusion

Wellsite J is best understood as a persistent, attenuated fugitive methane leakage system. Leakage is confirmed and environmentally meaningful, but current evidence does not indicate an acute high-impact receptor scenario. Natural attenuation substantially reduces atmospheric $CH_4$ expression, while also generating a broader $CO_2$, microbial, geophysical and geochemical footprint in near-field soils.

The recommended management position is structured monitored management with targeted, condition-aware reassessment and defined escalation triggers. This provides a proportionate middle ground between passive no-action and immediate intrusive remediation. The position should be revisited if future monitoring shows increasing emissions, weakening attenuation, footprint expansion, or new receptor exposure.

## 5. WP3: Knowledge Dissemination and Knowledge Building

Dissemination and knowledge transfer formed an important supporting component of this Phase 3 project. The project has generated a substantial set of scientific outputs from the Wellsite J investigations, including two major open-access journal publications to date: one in Geophysical Research Letters and one in Journal of Geophysical Research: Atmospheres. Both papers are available open access through university-supported publication routes, meaning they can be freely accessed and downloaded by researchers, regulators, industry practitioners, and other stakeholders. This is an important project outcome because it ensures that the methods, data interpretation, and broader lessons from Wellsite J are not restricted behind paywalls and can contribute directly to wider understanding of legacy well leakage, methane oxidation, and environmental monitoring. At least three further peer-reviewed papers are planned from the Phase 3 dataset, which are also expected to be published open access where possible.

The project findings have also been disseminated through conference presentations and abstracts. These include presentations at the European Geosciences Union General Assembly, where results from the Wellsite J multi-scale geophysical–geochemical footprint work and the continuous $CH_4$–$CO_2$ monitoring/atmospheric modulation work were presented. Additional dissemination within Canada has included a Canadian Geophysical Union abstract, focused on the geophysical manifestation of leakage emanating from wellsite J. These conference activities have helped place the BC OGRIS-supported Wellsite J work in front of international geoscience, atmospheric science, and environmental monitoring audiences, while demonstrating the wider relevance of the site as a field example of persistent but naturally attenuated legacy well leakage.

In addition to academic dissemination, Phase 3 has included targeted knowledge transfer to technical and practitioner audiences. A dedicated presentation was delivered to the Well Integrity and Abandonment Society on 28th May 2026, titled *"Legacy Well Leakage in British Columbia: What We've Learned, What We're Missing, and What It Means for Monitoring and Regulation"*, with an audience of approximately 50 attendees. This presentation was used to communicate the main project findings in a form directly relevant to well integrity, abandonment, leakage monitoring, and practical risk management. A further dedicated session with the British Columbia Energy Regulator is being developed / has been proposed for fall 2026, with the aim of presenting the Wellsite J findings directly to relevant regulatory and government stakeholders. This proposed session is intended to support uptake of the project outcomes within Canada and to position Wellsite J as a valuable provincial/national field case for understanding low-magnitude fugitive methane leakage, natural attenuation, and proportionate monitoring and management.

Together, these activities provide a strong dissemination pathway for Phase 3. The project has delivered high-quality open-access scientific publications, international and Canadian conference outputs, and targeted practitioner/regulator engagement. This combination ensures that the findings are communicated both through formal peer-reviewed science and through applied knowledge-transfer routes relevant to legacy well management in British Columbia.

## 6. Overall Phase 3 Project Findings and Implications

Phase 3 has delivered a substantial scientific and applied advance in understanding methane leakage behaviour and natural attenuation at integrity-compromised legacy wells in British Columbia and beyond. Building on earlier OGRIS-supported work, the project moved beyond the initial identification of leakage and the first demonstration of significant methane oxidation at Wellsite J toward a more mature, process-based understanding of how persistent low-level leakage is expressed, modified, and interpreted under natural field conditions. In this respect, the project has met its core objectives and, in several important ways, exceeded the original scientific opportunity anticipated at the outset.

The strongest outcome of Phase 3 lies in the advanced field investigations undertaken at Wellsite J. These investigations generated a broader and more integrated field dataset than had previously been available and have already yielded several key scientific outputs. Together, the findings show that Wellsite J is a persistent, structured, and dynamically expressed shallow environmental system. Leakage at the site produces a nested multi-scale footprint spanning direct methane flux, carbon dioxide expression, geophysical response, geochemical perturbation, microbiological indicators, and shallow-soil process evidence. Its surface expression is also strongly modified by methane oxidation and field conditions, such that direct methane emissions alone do not provide a complete or stable representation of site behaviour.

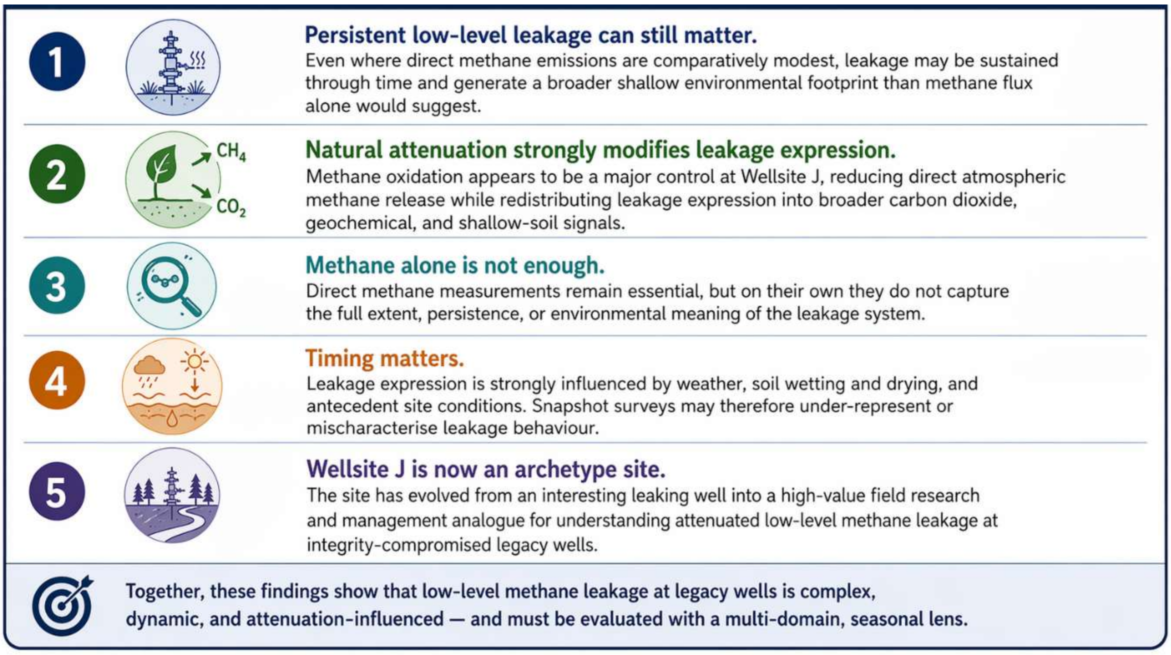
This has important implications for how low-level legacy-well leakage is interpreted. First, persistent low-level leakage should not be assumed to be environmentally trivial simply because direct methane emissions at the surface are modest. Even where atmospheric methane release is limited, sustained leakage may generate broader and longer-lived shallow environmental signatures. Second, natural attenuation, particularly methane oxidation, can materially alter the environmental meaning of leakage by reducing atmospheric methane loss while redistributing part of the leakage expression into carbon dioxide generation and shallow geophysical–geochemical response. Third, monitoring design and timing matter. Snapshot surveys, methane-only approaches, or measurements undertaken without reference to field conditions may under-represent the persistence, structure, or significance of leakage.

The WP2 environmental appraisal translated these scientific findings into a site-specific risk and management perspective. Using a source–pathway–receptor and weight-of-evidence approach, the appraisal concluded that Wellsite J is of low-to-moderate environmental significance under current evidence. The strongest complete linkages are to atmosphere/climate and shallow soils, while groundwater, surface water, vegetation, and human/safety receptors remain conditional under the present rural/agricultural setting. The recommended management posture is structured monitored management with targeted, condition-aware reassessment and defined escalation triggers, rather than either passive no-action or immediate intrusive remediation by default.

The project also generated value through dissemination and knowledge transfer. Phase 3 has already supported open-access scientific publications, conference presentations, and targeted engagement with professional and regulatory audiences. These activities help ensure that the findings from Wellsite J inform wider discussion around legacy well leakage, methane oxidation, monitoring design, environmental interpretation, and proportionate management in British Columbia and beyond.

Overall, Phase 3 should be regarded as a highly successful project. It has delivered a major field dataset, high-quality scientific outputs, a site-specific environmental management perspective, and a stronger evidential basis for understanding what persistent low-level methane leakage at a site such as

Wellsite J actually means. The principal message is that the environmental and management significance of such systems cannot be judged from methane emissions alone, but must be understood in the wider context of source persistence, natural attenuation, shallow environmental response, receptor exposure, and the field conditions under which leakage is expressed.




**Box 1:** Key messages from the Wellsite J Phase 3 investigation. Summary of the principal scientific and management-relevant findings from Phase 3, highlighting the persistence, attenuation-modified expression, multi-domain footprint, and condition-dependent behaviour of low-level methane leakage at Wellsite J.

## 7. Recommended Next Steps

Phase 3 has established Wellsite J as more than a successful project site. It is now a well-characterised field analogue for a class of legacy-well leakage that is likely to be important in British Columbia and elsewhere: persistent, low-to-moderate magnitude methane leakage that is strongly modified by natural attenuation and therefore difficult to interpret from methane measurements alone. This makes the site valuable not only for understanding one leaking well, but for developing more defensible approaches to detecting, interpreting, and managing attenuated leakage at other integrity-compromised wells.

The next stage of work should not aim to collect more data at Wellsite J for its own sake. Rather, it should use the site deliberately to answer a small number of management-relevant questions that arise directly from Phase 3. The most important of these are as follows.

1. **How does the leakage system behave during winter, snow-cover, frozen-ground, and spring freshet conditions?** Phase 3 successfully extended the observational record beyond the earlier summer-focused work, but the most conservative end-member for a northern British Columbia site remains incompletely characterised. For several months of the year, the site may experience snow cover, frozen or partially frozen ground, very low soil temperatures, and subsequent thaw/freshet conditions. These conditions are directly relevant to methane

oxidation, gas transport, soil moisture, and atmospheric expression. Targeted winter and freshet monitoring would therefore provide a critical test of whether the attenuation-modified interpretation developed from the current evidence remains valid under the conditions most likely to challenge biological oxidation and alter shallow gas transport. This would also help constrain whether summer, spring, or fall observations understate or adequately represent annual methane expression.

2. **What is the shallow pathway architecture between the buried well/source zone and the near-surface oxidation zone?** The current evidence is strongest in the near-surface, where direct flux, geophysical, geochemical, microbiological, and soil-state indicators all show a structured leakage footprint. A remaining question is how fugitive gas moves through the shallow subsurface between the buried wellhead/source area and the surface expression zone. Targeted deeper soil-gas, temperature, geophysical, and shallow subsurface profiling could help determine whether migration is highly focused, laterally distributed through disturbed backfill, influenced by moisture or textural horizons, or potentially capable of bypassing parts of the oxidation zone under certain conditions. This would strengthen interpretation of pathway stability and help distinguish a stable attenuated leakage system from one with greater potential for expansion, migration, or receptor linkage.

3. **What minimum evidence base is needed to classify and manage attenuated low-level leakage defensibly?** One of the clearest lessons from Phase 3 is that no single method fully captures the Wellsite J leakage system. Methane flux confirms direct atmospheric release, $CO_2$ helps indicate oxidative transformation, geophysics and geochemistry record broader shallow alteration, and soil-state observations provide context for environmental modulation. However, it will not be practical to apply the full Phase 3 scientific programme at every leaking well. A valuable next step would therefore be to use Wellsite J to identify a proportionate monitoring toolkit: the minimum combination of measurements needed to confirm leakage, recognise attenuation, assess footprint stability, and support a decision between monitored management, targeted investigation, mitigation, or remediation. This would directly support regulators and operators who need practical, defensible methods for managing multiple low-level leakage sites.

4. **Are the nested footprint and attenuation-modified expression observed at Wellsite J transferable to other leaking wells?** Wellsite J is now a strong archetype, but its broader management value depends on understanding which aspects of the model are site-specific and which are more general. A focused follow-on study could revisit one or two additional leaking wells identified during earlier OGRIS-supported screening and test whether similar nested footprints, $CH_4$–$CO_2$ relationships, geophysical/geochemical expressions, or attenuation signatures occur elsewhere. This need not become a broad regional screening exercise. A small number of carefully selected comparator sites would be sufficient to test transferability and begin distinguishing different low-level leakage archetypes. This would move the work from a single-site case study toward a more general framework for classifying attenuated leakage behaviour in British Columbia.

5. **Can Wellsite J serve as a field platform for testing monitoring technologies and management approaches?** Because Wellsite J is persistent, accessible, well characterised, and environmentally moderate rather than acute, it is well suited to method comparison and practical demonstration. The site could be used to evaluate alternative or complementary

approaches to leakage detection, including chamber flux methods, paired $CH_4$–$CO_2$ monitoring, soil-gas profiling, geophysical surveys, isotopic and geochemical diagnostics, continuous near-surface sensors, mobile or remote methane detection, and potentially vegetation or crop-response indicators. The value of such testing lies in the fact that the site represents a real, naturally attenuated leakage system rather than an artificial release experiment. Over time, this could support development of field protocols, training exercises, stakeholder demonstrations, and practical decision tools for legacy well assessment.

These questions are directly relevant to current and future management of legacy wells in British Columbia. They also have wider relevance to emerging subsurface containment and geoenergy contexts, including future carbon capture and storage, where legacy wells may represent potential leakage pathways and where monitoring, detection, attenuation, and proportionate response frameworks will be important. Wellsite J provides an opportunity to develop that understanding in a real field setting before such questions become more acute in operational contexts.

The recommended next step is therefore a focused follow-on phase centred on the theme of moving from characterisation to decision support. Such a phase would use Wellsite J to test the robustness of the current attenuation interpretation under winter and freshet conditions, refine understanding of shallow pathway architecture, identify practical monitoring requirements, and assess transferability to selected comparator wells. The intended outcome would not necessarily be additional scientific description, but a more operational framework for assessing attenuated low-level methane leakage: how to detect it, how to interpret it, how to monitor it, and how to decide whether continued monitored management or escalation is warranted.

Longer term, Wellsite J should be considered as a provincial field asset for understanding, monitoring, and managing attenuated fugitive gas release from legacy wells. The site has now reached a level of characterisation that is unusual for this type of leakage setting. Continued use of the site would support scientific publication, technology testing, method comparison, regulator and operator engagement, and training of highly qualified personnel. It would also help maintain British Columbia's position at the forefront of applied research into legacy well leakage, natural attenuation, and proportionate environmental management.

In closing, Phase 3 has created both a strong evidence base and a strategic opportunity. The immediate scientific question is no longer simply whether Wellsite J is leaking; that has been established. The more important next question is how this type of low-level, attenuated leakage should be evaluated and managed in practice. Wellsite J is uniquely well placed to answer that question and should be retained and developed as a targeted field platform for advancing practical, regulator-relevant understanding of legacy well leakage in British Columbia.

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## References:

1 Cahill, A. G. *et al.* Advancing knowledge of gas migration and fugitive gas from energy wells in northeast British Columbia, Canada. *Greenh Gases* **9**, 134-151, doi:10.1002/ghg.1856 (2019).

2 Dusseault, M. B. *et al.* in *International Oil and Gas Conference and Exhibition in China.*

3 Bachu, S. Analysis of gas leakage occurrence along wells in Alberta, Canada, from a GHG perspective - Gas migration outside well casing. *Int J Greenh Gas Con* **61**, 146-154, doi:10.1016/j.ijggc.2017.04.003 (2017).

4 Boothroyd, I. M. *et al.* Fugitive emissions of methane from abandoned, decommissioned oil and gas wells. *Sci Total Environ* **547**, 461-469, doi:10.1016/j.scitotenv.2015.12.096 (2016).

5 Schout, G. *et al.* Occurrence and fate of methane leakage from cut and buried abandoned gas wells in the Netherlands. *Sci Total Environ* **659**, 773-782, doi:https://doi.org/10.1016/j.scitotenv.2018.12.339 (2019).

6 Forde, O. N. *et al.* Identification, spatial extent and distribution of fugitive gas migration on the well pad scale. *Sci Total Environ* **652**, 356-366, doi:https://doi.org/10.1016/j.scitotenv.2018.10.217 (2019).

7 McMahon, P. B. *et al.* Methane in groundwater from a leaking gas well, Piceance Basin, Colorado, USA. *Sci Total Environ* **634**, 791-801, doi:https://doi.org/10.1016/j.scitotenv.2018.03.371 (2018).

8 Lackey, G. *et al.* A decade of progress in understanding and managing legacy well integrity for geologic carbon storage. *Int J Greenh Gas Con* **151**, 104604, doi:https://doi.org/10.1016/j.ijggc.2026.104604 (2026).

9 Pullen, B. *et al.* Differentiating legacy wellbores in the scottish north sea using multi-criteria decision analysis with a view to minimising containment risk for carbon capture and storage. *Int J Greenh Gas Con* **142**, 104336 (2025).

10 Cahill, A. G. *et al.* Evaluating Methane Emissions From Decommissioned Unconventional Petroleum Wells in British Columbia, Canada. *Geophysical Research Letters* **50**, e2023GL106496, doi:https://doi.org/10.1029/2023GL106496 (2023).

11 Cahill, A. G. *et al.* Natural soils-based oxidation mitigates methane leakage from integrity compromised legacy wells. *Geophysical Research Letters* **52**, e2024GL113522 (2025).

12 Cahill, A. G. *et al.* A Multi-Scale Geophysical–Geochemical Footprint of Persistent Methane Leakage at a Legacy Petroleum Well. *Geophysical Research Letters* **53**, e2026GL122657, doi:https://doi.org/10.1029/2026GL122657 (2026).

# APPENDIX A
# WP2: Site-Specific Environmental Risk Appraisal and Management Perspective

### WP2.1 Purpose and approach

The purpose of WP2 is to translate the scientific findings from the Wellsite J investigations into a concise, site-specific environmental risk appraisal and management perspective. The work is intended to support interpretation of the environmental significance of persistent fugitive methane leakage at the site and to identify a proportionate management response in light of the available evidence. It is not intended to constitute a full generic contaminated-land risk assessment or detailed remedial options appraisal. Rather, it provides a focused appraisal of Wellsite J as a confirmed but attenuated leakage system, using evidence generated through earlier BC OGRIS phases, the Phase 3 field investigations, and associated published analyses.

Wellsite J provides a useful case for this type of appraisal because it does not present simply as a high-flux point methane source. Previous investigations have shown that the site hosts persistent fugitive gas leakage from an integrity-compromised legacy well, but that the surface expression of this leakage is strongly modified by shallow soil processes. Methane emissions are spatially compact, carbon dioxide expression is broader, and multiple lines of evidence indicate substantial methane oxidation within the vadose zone before gas reaches the atmosphere. The site therefore represents an attenuated but active leakage archetype: a legacy well where leakage is real and persistent, but where natural attenuation materially modifies the magnitude, spatial expression, and environmental significance of the surface signal.

The appraisal adopts a proportionate source–pathway–receptor approach, supported by a weight-of-evidence interpretation of site-specific data. This framing is appropriate because the core management question is not whether leakage is present; this has already been established, but whether the source, migration pathways, attenuation processes, and receptor context indicate a level of environmental significance that warrants active intervention, structured monitoring, or a more precautionary management response. The approach is deliberately decision-facing, reflecting the supporting role of WP2 within the wider Phase 3 project.

Accordingly, WP2 evaluates Wellsite J using four linked questions:

1. What is the nature and persistence of the leakage source?
2. Through what pathways is fugitive gas migrating and being transformed?
3. Which receptors are plausibly exposed under the current site setting?
4. What management posture is proportionate given the observed magnitude, attenuation, footprint, receptor context, and uncertainty?

This appraisal therefore treats Wellsite J neither as environmentally trivial nor as an acute high-risk site by default. Instead, it assesses the site as a persistent, structured, dynamically expressed shallow leakage system for which management should be guided by source behaviour, attenuation performance, receptor exposure, and change through time.

## WP2.2 Evidence base for the appraisal

The environmental appraisal of Wellsite J is underpinned by a strong site-specific evidence base for a legacy well leakage setting. Across successive BC OGRIS-supported investigations, the site has been examined using repeated $CH_4$–$CO_2$ surface flux surveys, stable isotope measurements, shallow soil-gas profiling, soil geochemistry, microbiological analysis, geophysical mapping, continuous hotspot monitoring, and paired soil-state and meteorological observations. This evidence is sufficient to move beyond a binary interpretation of "leaking" or "not leaking" and to assess the site as a persistent, attenuated shallow leakage system with definable source behaviour, transport pathways, attenuation processes, and environmental expression.

The first key finding is that leakage at Wellsite J is confirmed and persistent. The site was initially identified in August 2022 as one of the clearest examples of potential integrity failure among the examined decommissioned unconventional wells in northeastern British Columbia. In that campaign, Wellsite J exhibited elevated $CH_4$ fluxes at the assumed wellhead location, elevated $CO_2$ fluxes relative to background, and stable isotope evidence consistent with a thermogenic gas source modified during transport through shallow soils. Site-wide excess greenhouse-gas emissions were estimated at approximately 1,991 kg $CO_2$-eq $yr^{-1}$. This was modest in absolute terms, but sufficiently distinct from background to confirm an active fugitive gas expression.

Subsequent work strengthened this interpretation by showing that the surface $CH_4$ signal represents only part of the leakage system. In 2023, average surface fluxes directly at the wellhead were approximately 13 µmol $m^{-2}$ $s^{-1}$ for $CH_4$ and 34 µmol $m^{-2}$ $s^{-1}$ for $CO_2$, compared with background values close to zero for $CH_4$ and approximately 3.2 µmol $m^{-2}$ $s^{-1}$ for $CO_2$. At 1 m depth, $CH_4$ fluxes were much higher, averaging approximately 192 µmol $m^{-2}$ $s^{-1}$, with a substantially higher $CH_4$:$CO_2$ ratio than at surface. This depth contrast provides direct field evidence that a significant fraction of upward migrating $CH_4$ is transformed before reaching the atmosphere.

The second key finding is that methane oxidation is a major control on the site's environmental expression. Multiple indicators support this interpretation, including inverse $CH_4$–$CO_2$ behaviour with depth, isotope evidence consistent with $CH_4$-derived $CO_2$, enriched residual $CH_4$ signatures consistent with biodegradation, and a distinct wellhead microbiome enriched in methanotroph-associated taxa. Mass-balance estimates from the 2023 investigation indicated high summer-condition $CH_4$ oxidation extents, of the order of ~90%, with method-specific oxidation-rate estimates ranging from approximately 33 to 248 g $CH_4$ $m^{-2}$ $d^{-1}$. These values indicate that natural soils at Wellsite J are functioning as an active biofilter for fugitive $CH_4$ under favourable conditions.

However, attenuation should not be treated as constant. Reactive transport modelling using Wellsite J-specific inputs indicated that oxidation and emissions are likely to vary strongly across the annual cycle, primarily due to seasonal temperature effects. The model suggested that $CH_4$ oxidation may approach near-total conversion during favourable summer periods but fall substantially during winter, with annual average oxidation more plausibly closer to approximately 40% than the >90% inferred from peak summer field conditions alone. This distinction is central to WP2 because the site's significance depends on both persistent source activity and condition-dependent attenuation capacity.

The third major finding is that Wellsite J has a nested, multi-scale shallow footprint. Surface $CH_4$ expression is spatially compact and centred on the wellhead area, whereas $CO_2$, geophysical, and geochemical responses extend farther from the source. April 2025 data show that the combined surface gas flux signal attenuates very rapidly with distance, with a characteristic half-distance of approximately ~0.1 m. In contrast, electromagnetic conductivity data define a co-centred but broader geophysical anomaly with a characteristic half-distance of approximately ~2 m, and soil geochemical indicators remain elevated across the near-field zone of ~4 m before returning to background at the distal reference location. This indicates that persistent leakage has reorganised shallow soil conditions over a larger area than would be inferred from $CH_4$ flux alone.

The fourth major finding is that short-term flux expression is dynamic and condition-dependent. High-resolution 2025 monitoring showed that $CH_4$ emissions formed a compact and persistent hotspot, typically of the order of ~1 m², while $CO_2$ formed a broader and more variable footprint of approximately ~30 m². Average integrated emissions during the multi-day monitoring period were approximately 19 g $CH_4$ d$^{-1}$ and 446 g $CO_2$ d$^{-1}$, equivalent to approximately 2.03 kg $CO_2$-eq d$^{-1}$, or 0.74 t $CO_2$-eq yr$^{-1}$ if sustained continuously under those conditions. Continuous monitoring also showed that fluxes vary over timescales of hours to days, with baseline behaviour linked to soil thermal–hydrological conditions and atmospheric forcing, while some episodic high-flux events likely reflect transient subsurface source behaviour.

Together, the evidence base indicates that Wellsite J should be appraised as a confirmed, persistent, low-to-moderate magnitude fugitive methane leakage site where direct atmospheric $CH_4$ emissions are substantially mitigated by near-surface oxidation, but where the leakage source remains active and generates a measurable shallow environmental footprint. The most relevant evidence for WP2 is summarised in Table 2.1.

**Table 1: Evidence base and relevance to the Wellsite J environmental risk appraisal**

| Evidence domain | Main site-specific observations | Quantitative / semi-quantitative constraints | Relevance to risk appraisal |
|---|---|---|---|
| **Site setting and well context** | Decommissioned, cut/capped/buried legacy gas well in active agricultural land near the Cecil Lake / Fort St. John region. | Well cut and buried approximately 2–3 m below ground surface; active rural/agricultural setting. | Receptor setting is open rural/agricultural rather than urban or enclosed. Human safety receptors are limited under current land use, but atmosphere, shallow soils, and land-management receptors remain relevant. |
| **Source confirmation and persistence** | Repeated $CH_4$ and $CO_2$ anomalies centred on the wellhead area; thermogenic $CH_4$ signature; persistent expression across 2022, 2023, and 2025 investigations. | 2022 maximum $CH_4$ flux ~3.01 μmol m$^{-2}$ s$^{-1}$; maximum $CO_2$ flux ~28.86 μmol m$^{-2}$ s$^{-1}$; $\delta^{13}C$-$CH_4$ ~−33.7‰; multi-year recurrence of centred anomalies. | Confirms an active fugitive gas source rather than isolated background variability. Persistence elevates management relevance even where emissions are modest. |
| **Surface $CH_4$ expression** | $CH_4$ expression is compact and spatially focused near the leakage centre. | 2025 spatial surveys: $CH_4$ excess footprint typically ~1 m²; median hotspot $CH_4$ flux ~40.5 μmol m$^{-2}$ s$^{-1}$; peaks up to ~79.4 μmol m$^{-2}$ s$^{-1}$ in spatial surveys; episodic continuous-monitoring events >400 μmol m$^{-2}$ s$^{-1}$. | Direct $CH_4$ emissions are real but highly localised. Coarse or poorly located surveys could miss or under-characterise the source. |
| **$CO_2$ expression and oxidation signal** | $CO_2$ expression is broader than $CH_4$ and interpreted mainly as an oxidation-related secondary signal | 2025 $CO_2$ footprint typically ~30 m²; $CO_2$ elevated up to ~4 m from the hotspot; 2023 average surface $CO_2$ flux at wellhead ~34 μmol | $CO_2$ is a key diagnostic of attenuation and shallow transformation. $CH_4$-only appraisal |

| | | | |
|---|---|---|---|
| | rather than simple background respiration. | $m^{-2}$ $s^{-1}$ versus background ~3.2 µmol $m^{-2}$ $s^{-1}$. | would understate the full environmental expression of leakage. |
| **Depth profile and vadose-zone attenuation** | $CH_4$ fluxes at 1 m depth are much higher than at surface, while $CH_4$:$CO_2$ ratio decreases sharply toward ground surface. | 2023 average $CH_4$ flux ~192 µmol $m^{-2}$ $s^{-1}$ at 1 m depth versus ~13 µmol $m^{-2}$ $s^{-1}$ at surface; $CH_4$:$CO_2$ ratio ~6.0 at 1 m versus ~0.43 at surface. | Strong evidence for vertical attenuation through the vadose zone. The leakage source is larger than surface $CH_4$ alone suggests. |
| **Methane oxidation and seasonality** | Multiple indicators show substantial $CH_4$ oxidation, but oxidation is condition-dependent and seasonally variable. | Estimated oxidation extent ~94%; oxidation rates ~33 to ~248 g $CH_4$ $m^{-2}$ $d^{-1}$ depending on method; modelling suggests >10× variation in emissions across the annual cycle and annual average oxidation closer to ~40%. | Attenuation materially reduces atmospheric $CH_4$ impact but does not eliminate source activity. Management should be seasonally aware. |
| **Greenhouse-gas magnitude** | Emissions are persistent but modest in absolute terms relative to larger fugitive or agricultural GHG sources. | 2022 estimate ~1.99 t $CO_2$-eq $yr^{-1}$; 2023 summer-condition estimate ~7.14 t $CO_2$-eq $yr^{-1}$; 2025 multi-day estimate ~0.74 t $CO_2$-eq $yr^{-1}$ if continuous under observed conditions. | Supports classification as low-to-moderate environmental significance rather than severe atmospheric impact, while retaining concern over persistence and uncertainty. |
| **Geophysical and geochemical footprint** | EM conductivity anomaly and soil geochemical response are co-centred with the leakage source but extend beyond the compact flux core. | April 2025: surface flux half-distance ~0.12 m; EM conductivity half-distance ~2.05 m; Soil Leakage Index elevated across 0–4 m near-field locations and returns to background at ~60 m reference. | Indicates a metre-scale shallow alteration zone associated with persistent leakage. Flux alone under-represents footprint extent. |
| **Microbiological evidence** | Wellhead soils differ from background soils, with enrichment of methane-oxidation-associated microbial groups. | 2025 paper reports dominant methanotroph-associated consortia and reduced/divergent microbial diversity at wellhead soils. | Supports biological attenuation and confirms that leakage has altered the shallow soil ecosystem locally. |
| **Environmental modulation and transient behaviour** | Flux magnitude varies with soil moisture, temperature, and atmospheric forcing; some high-flux events likely reflect transient subsurface source dynamics. | 2025 continuous monitoring: ~70 h hotspot monitoring; strong $CH_4$–$CO_2$ temporal correlation; episodic events >400 µmol $m^{-2}$ $s^{-1}$ $CH_4$ and >80 µmol $m^{-2}$ $s^{-1}$ $CO_2$. | Snapshot measurements can misrepresent site behaviour. Monitoring design should account for environmental state and transient source behaviour. |
| **Current receptor evidence** | No current evidence has been identified of acute human safety, groundwater, or severe ecological impact under the rural/agricultural land-use setting. | Evidence primarily demonstrates atmospheric emission, shallow soil-gas transformation, geophysical/geochemical alteration, and microbiological response. | Supports a proportionate management posture focused on structured monitoring and escalation triggers rather than immediate emergency intervention. |

Overall, Table 2.1 supports three conclusions for the WP2 appraisal. First, Wellsite J is a genuine and persistent fugitive gas leakage site. Second, the primary environmental expression is not a large direct $CH_4$ plume, but a coupled $CH_4$–$CO_2$–soil system in which oxidation strongly modifies the surface signal. Third, methane magnitude alone does not capture environmental significance: the atmospheric burden appears modest, but the broader shallow footprint confirms sustained interaction between fugitive gas leakage and the near-surface environment. This evidence base provides the foundation for the source–pathway–receptor appraisal developed in the following section.

## WP2.3 Conceptual site model and source–pathway–receptor appraisal

A concise conceptual site model was developed to support the source–pathway–receptor appraisal for Wellsite J. The model reflects the current weight of evidence that the site is affected by persistent fugitive gas leakage from an integrity-compromised legacy well, but that the surface expression of this leakage is strongly modified by shallow soil processes. Upward migrating $CH_4$ is partially oxidised within the vadose zone, producing a compact $CH_4$ emission core, a broader $CO_2$ expression, and a wider geophysical–geochemical–microbiological footprint in shallow soils. The resulting environmental system is therefore not adequately represented by $CH_4$ flux alone.

The conceptual model is shown in Figure 2.1. It is intentionally simple and site-specific. Its purpose is not to exhaustively characterise all possible subsurface processes, but to identify the principal source, pathways, attenuation processes, receptors, and management implications relevant to Wellsite J under the current evidence base. The model should be treated as a current-evidence model rather than a fixed site classification and should be revisited if leakage magnitude, attenuation performance, land use, or receptor exposure changes.

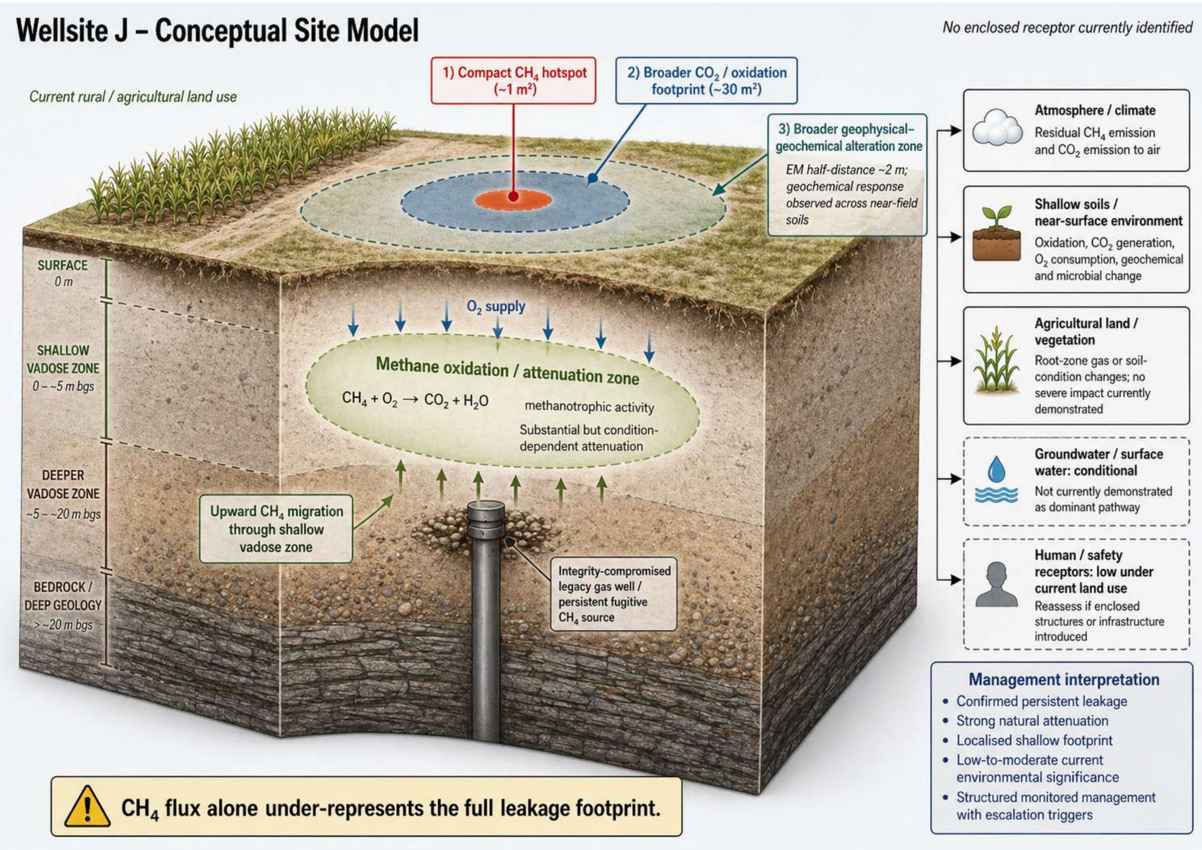


**Figure 1: Conceptual site model for Wellsite J.** Persistent fugitive $CH_4$ leakage from an integrity-compromised buried legacy well migrates upward through the shallow vadose zone, where substantial but condition-dependent methane oxidation attenuates atmospheric $CH_4$ release and generates a broader $CO_2$ and shallow alteration footprint. The resulting environmental expression is nested: a compact $CH_4$ hotspot, broader $CO_2$/oxidation footprint, and broader geophysical–geochemical response in near-field soils. Current receptor linkages are strongest for atmosphere/climate and shallow soils, while groundwater, surface water, and human/safety receptors are conditional under the present rural/agricultural land-use setting.

The conceptual model leads to a focused SPR appraisal. The primary complete linkage is from the compromised legacy well to the atmosphere via shallow gas migration, partial methane oxidation, and residual surface emission. A second complete linkage exists between the leakage source and the shallow soil system, where methane oxidation, $CO_2$ generation, oxygen consumption, geochemical alteration, and microbial response occur within the near-surface. Other receptors, including vegetation, groundwater, surface water, and human/safety receptors, are retained as conditional linkages because they are plausible in principle but not currently demonstrated as dominant risk drivers under the present site setting.

The source–pathway–receptor appraisal is summarised in Table 2.

**Table 2: Source–pathway–receptor appraisal for Wellsite J**

| Source | Pathway / modifying process | Receptor | Evidence basis | Current significance |
|---|---|---|---|---|
| Fugitive $CH_4$ leakage from integrity-compromised legacy well | Upward gas migration through the shallow vadose zone; incomplete oxidation; residual $CH_4$ emission at surface. | Atmosphere / climate impacts | Persistent $CH_4$ flux across repeated campaigns; compact $CH_4$ hotspot centred on wellhead area; 2025 monitoring indicates ~1 m² hotspot and modest integrated GHG burden under observed conditions. | **Low to moderate.** Real and persistent atmospheric release, but modest relative to high-emission leakage scenarios. |
| Fugitive $CH_4$ leakage from legacy well | Upward transport through vadose zone; microbial oxidation of $CH_4$ to $CO_2$; decreasing $CH_4$:$CO_2$ ratio toward surface. | Vadose-zone gas system / shallow soil gas | $CH_4$ flux at 1 m depth is substantially higher than at surface, while $CO_2$ becomes more prominent toward surface. | **Moderate.** Active pathway with substantial transformation before surface release. |
| Leakage-derived $CH_4$ undergoing oxidation | $CO_2$ generation and broader surface expression than $CH_4$. | Atmosphere / shallow surface environment | $CO_2$ footprint is broader and more variable than $CH_4$; 2025 monitoring indicates ~30 m² $CO_2$ footprint compared with ~1 m² $CH_4$ hotspot. | **Moderate, localised.** Indicates methane transformation and broader shallow influence, but not severe receptor impact. |
| Fugitive gas leakage and methane oxidation | Modification of pore gas, redox/geochemical conditions, moisture/electrical properties, and solute redistribution. | Shallow soils / near-surface subsurface | Geophysical and geochemical responses extend beyond compact flux core; April 2025 half-distances of ~0.12 m for flux and ~2.05 m for EM conductivity. | **Moderate, localised.** Measurable shallow alteration, but footprint appears local to the well area. |
| Fugitive $CH_4$ leakage supporting methanotrophy | Biological methane oxidation and associated microbial community shift. | Soil microbial community / shallow soil ecosystem | Wellhead soils differ from background and are enriched in methane-oxidation-associated microbial communities. | **Moderate, localised.** Supports active biological attenuation and local soil ecosystem response. |
| Fugitive gas leakage and oxidation products | Root-zone gas alteration, possible $O_2$ depletion, $CO_2$ enrichment, and local soil-condition change. | Agricultural soil / vegetation / crop condition | Active agricultural setting; gas flux, oxidation, and shallow alteration are demonstrated, but severe crop or vegetation impact is not. | **Low to uncertain.** Plausible receptor, but not currently a demonstrated risk driver. |
| Fugitive gas migration / leakage- | Potential dissolved gas migration or secondary geochemical impact if | Groundwater | Current evidence primarily concerns vadose-zone transport and near-surface alteration; no | **Low to uncertain.** Conditional pathway; should not be over- |

| | | | | |
|---|---|---|---|---|
| derived geochemical alteration | hydraulic connection exists. | | clear groundwater impact has been established. | weighted without hydrogeological evidence. |
| Fugitive gas migration / shallow soil-gas redistribution | Potential migration to drains, ditches, or surface-water features if local connectivity exists. | Surface water | No dominant surface-water linkage has been identified from current evidence. | **Low under current evidence.** Not a primary receptor unless drainage or surface-water connectivity is demonstrated. |
| Fugitive $CH_4$ migration | Potential accumulation in enclosed spaces, utilities, or confined infrastructure if receptors exist or are introduced. | Human health / safety | Current rural/agricultural setting; no evidence of enclosed-space accumulation, occupied structures, or acute explosive hazard near hotspot. | **Low under current land use.** Context-dependent; significance would increase if enclosed receptors were introduced. |

The SPR appraisal indicates that the complete and currently material linkages are those connecting the legacy well source to the atmosphere and shallow soils through vadose-zone gas migration and oxidation. These linkages are supported by repeated flux measurements, depth-profile evidence, isotope and microbial indicators, continuous monitoring, and the nested geophysical–geochemical footprint. The strongest environmental concern is therefore not acute toxicity or immediate safety impact, but the persistence of active leakage and its measurable alteration of the shallow subsurface.

The site's environmental significance is moderated by three factors: direct $CH_4$ expression is spatially compact; methane oxidation substantially reduces atmospheric $CH_4$ emissions under favourable conditions; and current receptor exposure is limited by the rural/agricultural setting and absence of evidence for enclosed-space, groundwater, surface-water, or severe vegetation impacts. These factors support a proportionate interpretation, but they do not justify dismissing the site as insignificant because the source is persistent and the shallow footprint is demonstrably structured.

On this basis, the conceptual site model for Wellsite J is best described as a persistent, localised, naturally attenuated leakage system. The site is active and environmentally relevant, but its current risk profile is dominated by low-to-moderate atmospheric emissions, localised shallow soil perturbation, and uncertainty around attenuation stability through time, rather than by acute receptor impact. This interpretation provides the basis for the attenuation-adjusted appraisal developed in the following section.

### WP2.4 Attenuation-adjusted interpretation

The SPR appraisal at Wellsite J requires explicit adjustment for attenuation because the site is not adequately described by direct $CH_4$ emission alone. The evidence indicates that fugitive $CH_4$ is released below ground from the compromised legacy well, migrates upward through shallow soils, and is substantially transformed before reaching the atmosphere. Natural attenuation is therefore not a secondary or speculative process at this site; it is a primary control on the observed environmental expression.

The principal attenuation mechanism is aerobic methane oxidation within the vadose zone. This process converts a portion of migrating $CH_4$ to $CO_2$ through microbial activity, reducing the mass of

$CH_4$ reaching the atmosphere. Previous work at Wellsite J estimated high oxidation extents under favourable summer conditions, with rates indicating that natural soils can function as an active biofilter for fugitive $CH_4$. This is beneficial from a greenhouse-gas perspective because conversion of $CH_4$ to $CO_2$ materially reduces the climate significance of the release compared with an equivalent unattenuated methane source.

For risk appraisal, the key implication is that surface $CH_4$ flux is not equivalent to leakage source strength. A compact or low $CH_4$ surface expression can reflect effective oxidation during upward migration rather than absence of leakage. This interpretation is supported by the observed $CH_4$–$CO_2$ depth relationships, broader $CO_2$ expression relative to $CH_4$, isotope evidence for $CH_4$-derived $CO_2$, and microbiological evidence for active methanotrophy. A $CH_4$-only assessment would therefore risk underestimating both source persistence and the broader shallow environmental footprint.

Attenuation modifies environmental significance in two directions. First, it reduces direct atmospheric $CH_4$ burden, supporting the interpretation that the site's current greenhouse-gas significance is low to moderate rather than severe. Second, it creates a broader shallow environmental expression, because $CH_4$ oxidation generates $CO_2$, consumes $O_2$, supports methanotrophic activity, and is associated with geophysical and geochemical alteration in near-field soils. In this sense, attenuation reduces one component of risk while making the shallow subsurface part of the environmental footprint.

This distinction is important for management. Natural attenuation should not be interpreted as source removal. The well remains an active source, and the shallow soils are functioning as a reactive filter between the source and the atmosphere. The management relevance of attenuation therefore depends on whether this filter remains effective under changing source loading, soil moisture, temperature, and seasonal conditions.

The attenuation capacity at Wellsite J is also condition-dependent. The strongest oxidation evidence was obtained under favourable summer conditions, while modelling and field interpretation indicate that lower temperatures or less favourable soil conditions may reduce oxidation and increase atmospheric $CH_4$ expression during other parts of the year. This does not invalidate the attenuation interpretation, but it means that attenuation should be treated as a dynamic, verified management-relevant process rather than a fixed site property.

For WP2, the attenuation-adjusted interpretation is therefore straightforward: Wellsite J is an active leakage site whose direct atmospheric $CH_4$ expression is substantially moderated by natural soils-based oxidation, but whose source remains persistent and environmentally relevant. The appropriate management questions are not whether methane is detectable at high flux at the surface, but whether leakage remains stable, whether attenuation remains effective, whether the shallow footprint remains localised, and whether any receptors become more exposed over time.

Overall, attenuation is beneficial and material at Wellsite J, but it is not a reason to dismiss the site. It supports a proportionate risk posture in which the site is managed as a persistent, attenuated leakage system with low-to-moderate atmospheric significance, a measurable shallow footprint, and a need for structured monitoring rather than passive no-action or automatic intrusive remediation.

### WP2.5 Overall environmental significance

The overall environmental significance of Wellsite J is best interpreted as low to moderate under the current evidence base. This classification reflects a balance between three findings: fugitive gas leakage is confirmed and persistent; direct atmospheric $CH_4$ expression is spatially compact and modest in total greenhouse-gas terms; and the leakage has generated a measurable shallow environmental footprint through methane oxidation, $CO_2$ generation, geophysical response, geochemical alteration, and microbial community change.

The site should therefore not be described as environmentally negligible. The source is real, has been observed across multiple investigations, and is spatially anchored to the legacy well location. Repeated $CH_4$–$CO_2$ flux measurements, depth-profile evidence, isotope interpretation, microbiological response, and the broader geophysical–geochemical footprint all support the conclusion that Wellsite J is an active shallow leakage system rather than background soil gas variability alone.

At the same time, the available evidence does not support classification of Wellsite J as an acute or severe environmental impact site. Detailed 2025 monitoring indicates a compact $CH_4$ hotspot of approximately ~1 m² and a broader $CO_2$ footprint of approximately ~30 m². Integrated multi-day emissions were estimated at approximately 19 g $CH_4$ $d^{-1}$ and 446 g $CO_2$ $d^{-1}$, equivalent to approximately 0.74 t $CO_2$-eq $yr^{-1}$ if sustained continuously under the observed conditions. These values indicate persistent emissions, but not a large site-scale greenhouse-gas source relative to high-emission well leakage scenarios.

The main environmental significance of Wellsite J therefore lies less in the absolute magnitude of direct $CH_4$ emissions and more in the persistence and structure of the shallow leakage system. The surface $CH_4$ expression is compact, but $CO_2$, geophysical, geochemical, and microbiological signals extend over a broader near-field area. This indicates that fugitive gas migration and oxidation have measurably altered shallow soil conditions around the well, even where direct methane flux is limited. The site is therefore best interpreted as a localised shallow environmental perturbation rather than a severe or widespread contamination problem.

From a receptor perspective, the strongest current linkages are to the atmosphere and shallow soils. Agricultural land and vegetation are plausible receptors, but severe crop or vegetation impact has not been demonstrated. Groundwater and surface water remain conditional receptors: they should be retained in the conceptual model, but are not currently demonstrated as dominant or complete risk pathways. Human health and safety receptors also appear limited under the present rural/agricultural land-use setting, with no current evidence of enclosed-space accumulation or acute explosive hazard. This conclusion should be revisited if land use changes, infrastructure is introduced, or monitoring indicates migration beyond the currently characterised near-field zone.

A concise significance summary is provided in Table 2.3.

**Table 2.3. Overall environmental significance summary for Wellsite J**

| Appraisal domain | Current interpretation | Significance |
|---|---|---|
| **Source status** | Confirmed persistent fugitive gas leakage from an integrity-compromised legacy well. | **Moderate** |
| **Direct atmospheric $CH_4$ emission** | Real and persistent but spatially compact; total observed GHG burden is modest under measured conditions. | **Low to moderate** |
| **Natural attenuation** | Substantial methane oxidation reduces atmospheric $CH_4$ expression, especially under favourable conditions. | **Beneficial, but condition-dependent** |
| **$CO_2$ / oxidation expression** | Broader than $CH_4$ and diagnostic of shallow methane transformation. | **Moderate, localised** |

| | | |
|---|---|---|
| **Shallow soil footprint** | Geophysical, geochemical, and microbiological indicators show measurable near-field alteration. | **Moderate, localised** |
| **Agricultural / vegetation receptor** | Plausible receptor, but no severe impact demonstrated from the current evidence. | **Low to uncertain** |
| **Groundwater / surface water receptors** | Not currently demonstrated as dominant or complete pathways. | **Low to uncertain** |
| **Human / safety receptor** | Low under current open rural/agricultural land use; context-dependent if land use changes. | **Low at present** |
| **Overall site significance** | Active, persistent, attenuated leakage system with modest atmospheric burden and localised shallow footprint. | **Low to moderate** |

On this basis, Wellsite J should be regarded as an environmentally meaningful but proportionate-risk site. The leakage is confirmed and persistent, so it warrants management attention and should not be dismissed. However, the current evidence does not indicate an acute, severe, or extensive receptor-impact scenario. The most appropriate classification is therefore low-to-moderate environmental significance, conditional on continued attenuation effectiveness, stable spatial footprint, and absence of new receptor exposure.

This interpretation is important beyond Wellsite J. The site illustrates that legacy well leakage should not be assessed solely on instantaneous surface $CH_4$ flux. A leaking well may have low direct methane expression because natural soils are acting as a reactive filter, while still producing a broader shallow environmental footprint. For management purposes, the key question is therefore whether the leakage system is persistent, whether attenuation remains effective, whether the footprint is stable, and whether receptors remain protected.

### WP2.6 Management options and reduced-order decision appraisal

The management response for Wellsite J should be proportionate to the observed risk profile and to the confidence provided by the current evidence base. The site is not a “no issue” location: fugitive gas leakage is confirmed, persistent, and associated with a measurable shallow environmental footprint. However, the evidence also does not indicate an acute high-risk scenario requiring immediate intrusive intervention by default. The appropriate management question is therefore not whether leakage exists, but what level of response is justified given the magnitude of emissions, spatial extent of the footprint, effectiveness of attenuation, receptor setting, uncertainty, and potential disturbance associated with remedial action.

This appraisal uses a reduced-order, MCDA-informed decision framework rather than a full numerical multi-criteria scoring model. This is appropriate because WP2 is intended to provide a site-specific environmental risk and management appraisal for Wellsite J, not a generic ranking tool for all leaking wells. The approach reflects the Phase 3 commitment to evaluate source–pathway–receptor linkages and identify a proportionate management strategy, while avoiding false precision where formal weighting factors and numerical thresholds are not established for this fugitive gas context.

The decision appraisal was undertaken in two steps. First, the site condition was assessed using criteria that reflect the main controls on environmental significance: source persistence, atmospheric emission magnitude, spatial footprint, attenuation effectiveness, receptor exposure, and residual uncertainty.

Second, the resulting site condition was mapped to a proportionate management response. This keeps the appraisal evidence-led: management options are considered in relation to the specific leakage behaviour and receptor context observed at Wellsite J.

The realistic management options form a simple intervention ladder of well classes:

1. **No further action / administrative closure**: appropriate only where no material leakage or receptor linkage is confirmed.
2. **Structured monitored management**: periodic targeted monitoring, condition-aware interpretation, and defined escalation triggers.
3. **Targeted further investigation or mitigation**: focused work to resolve specific uncertainty or reduce a defined risk pathway.
4. **Full intrusive remediation / re-entry / re-abandonment**: active intervention to attempt source reduction or elimination.
5. **Emergency intervention**: reserved for acute safety or receptor-impact conditions.

For Wellsite J, the decision question is where the site sits on this ladder under the current evidence base. The reduced-order site-condition appraisal is summarised in Table 2.4.

**Table 2.4. Reduced-order site-condition appraisal for Wellsite J**

| Decision criterion | Low concern | Moderate concern | High concern | Wellsite J interpretation |
|---|---|---|---|---|
| **Source status and persistence** | No confirmed source or anomaly consistent with background conditions. | Intermittent, uncertain, or weakly constrained leakage source. | Confirmed persistent leakage from a fixed source. | **High persistence.** Leakage is confirmed across repeated campaigns and spatially anchored to the legacy well location. This prevents the site being treated as background or administratively closed. |
| **Emission magnitude / atmospheric burden** | Low total flux and low greenhouse-gas burden. | Persistent measurable emissions or episodic moderate fluxes. | High sustained emissions or frequent high-flux events. | **Low to moderate.** $CH_4$ emission is real and persistent, but direct atmospheric burden is modest relative to high-emission leakage scenarios. |
| **Spatial footprint / extent** | Highly constrained near-source expression. | Local metre-scale footprint. | Extensive, expanding, poorly bounded, or >10 m-scale footprint. | **Moderate but localised.** $CH_4$ expression is compact, but $CO_2$, geophysical, and geochemical responses extend beyond the surface flux core. The multi-scale footprint remains centred on the well and appears near-field rather than extensive. |
| **Attenuation effectiveness and stability** | Attenuation demonstrated and stable under relevant conditions. | Attenuation demonstrated but condition-dependent. | Attenuation weak, absent, overwhelmed, or unverified. | **Moderate concern / beneficial but condition-dependent.** Methane oxidation is substantial and beneficial, but field interpretation and modelling indicate seasonal controls on oxidation performance. |

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|---|---|---|---|---|
| **Receptor exposure** | No sensitive receptor currently exposed; open land use; no demonstrated groundwater, surface-water, or safety linkage. | Plausible or conditional receptor pathway requiring review. | Sensitive receptor exposed or impacted, including human safety, groundwater, surface water, or severe ecological/agricultural impact. | **Low under current land use, with conditional receptors retained.** Current linkages are strongest for atmosphere and shallow soils. Agricultural land/vegetation, groundwater, surface water, and human/safety receptors remain conditional rather than demonstrated dominant risk drivers. |
| **Uncertainty and confidence** | Evidence base sufficient and uncertainty bounded. | Key uncertainties remain but are manageable through targeted monitoring. | Evidence insufficient to classify footprint, attenuation, source strength, or receptor exposure. | **Moderate but bounded.** The evidence base is unusually strong for a legacy well leakage site, but seasonal attenuation performance, long-term stability, and receptor change remain management-relevant uncertainties. |

The classes used here are appraisal categories developed for this site-specific decision context and are not intended to represent formal regulatory classifications. The resulting site-condition classification is:

**Class 2: confirmed but constrained / attenuated leakage**, with targeted uncertainty around seasonal attenuation performance and long-term footprint stability.

In this reduced-order framework, a Class 2 site is one where leakage is confirmed and persistent, but emissions are low to moderate, the footprint is localised, attenuation is demonstrated, and receptor exposure is limited under current conditions. This classification is important because Wellsite J scores high for source persistence, but not for current emission magnitude, receptor exposure, or footprint extent. It is therefore not suitable for no further action, because the source is persistent and the footprint is measurable. Equally, it does not currently meet a high-significance or acute-impact class that would make intrusive remediation the default response.

The classification provides the basis for comparing available management responses (Table 2.5). The purpose of this comparison is not to rank options numerically, but to identify which response is proportionate to a confirmed, attenuated, localised leakage site with specific remaining uncertainties.

**Table 2.5. Management response appraisal for Wellsite J**

| Management response | Fit to current evidence | Rationale | Recommended role |
|---|---|---|---|
| **No further action / administrative closure** | Poor fit. | Leakage is confirmed, persistent, and associated with a measurable shallow footprint. This option would underplay source persistence and provide no basis to verify attenuation stability or receptor change. | **Not recommended.** |
| **Structured monitored management** | Best fit. | Matches confirmed persistent leakage, compact $CH_4$ expression, localised footprint, substantial attenuation, and limited current receptor exposure. Maintains stewardship while allowing proportionate escalation. | **Recommended primary management posture.** |

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| **Targeted further investigation** | Conditional fit. | Useful where it addresses a specific management uncertainty, especially seasonal attenuation, footprint stability, or possible receptor linkage. Inefficient if broad or unfocused. | **Recommended only where targeted to a defined uncertainty.** |
| **Targeted mitigation / enhanced attenuation support** | Conditional fit. | Potentially relevant if monitoring shows attenuation is weakening, soil conditions are suppressing oxidation, or the footprint is expanding but remains manageable. Not currently required. | **Retain as an intermediate escalation option.** |
| **Full intrusive remediation / re-entry / re-abandonment** | Not justified as immediate default. | May reduce or remove the source if successful, but has the highest cost and disturbance and may disrupt agricultural soils and the existing attenuation zone. More proportionate if emissions increase, footprint expands, or receptors are affected. | **Retain as an escalation option.** |
| **Emergency intervention** | Poor fit under current evidence. | No acute enclosed-space, explosive, groundwater, surface-water, or severe ecological receptor trigger has been demonstrated. Appropriate only if acute safety or receptor-impact conditions emerge. | **Not indicated at present; retain as contingency.** |

The preferred management posture is therefore **structured monitored management**, supported by targeted reassessment of remaining uncertainties. This position is not equivalent to "do nothing." It recognises that the well remains an active source and that the shallow soils are functioning as a reactive attenuation zone. The management objective is to verify that the current risk posture remains valid: emissions remain low to moderate, the $CH_4$ hotspot remains compact, the broader $CO_2$/geophysical/geochemical footprint remains localised, attenuation remains effective under variable conditions, and no new receptor pathway becomes material.

This approach also avoids premature full remediation. Intrusive re-entry or re-abandonment would become more proportionate if monitoring showed increasing emissions, declining attenuation performance, footprint expansion, groundwater or surface-water involvement, severe vegetation or soil-function impacts, or the introduction of enclosed human/safety receptors. In the absence of such triggers, immediate intrusive remediation would represent a higher level of intervention than is currently supported by the evidence.

The practical decision logic can be summarised as follows: **Wellsite J is a Class 2 site with confirmed persistent leakage, but constrained, attenuated, and currently without demonstrated acute receptor impact. Structured monitored management is therefore the preferred current response, with targeted investigation, mitigation, or remediation reserved for defined escalation conditions.**

This provides a defensible bridge between the ERA and the management recommendation. It keeps the appraisal proportionate, recognises the confirmed leakage source, accounts for natural attenuation, and avoids treating all leaking legacy wells as environmentally equivalent.

### WP2.7 Recommended management position and escalation triggers

Based on the reduced-order decision appraisal, Wellsite J is classified as a Class 2 confirmed but constrained / attenuated leakage site, with targeted uncertainty around seasonal attenuation performance and long-term footprint stability. The recommended management position is therefore structured monitored management, supported by condition-aware reassessment and defined escalation triggers.

The management objective is not to prove repeatedly that the site is leaking; that has already been established. The objective is to verify that the current risk posture remains valid. For practical purposes, this means confirming that four conditions continue to hold:

1. the $CH_4$ emission hotspot remains spatially compact and within the established range of magnitude;
2. the $CO_2$/oxidation footprint remains consistent with effective shallow attenuation rather than expanding uncontrolled leakage;
3. the broader geophysical–geochemical footprint remains localised and stable;
4. no new receptor exposure emerges through land-use change, infrastructure development, groundwater connection, surface-water linkage, or ecological impact.

A proportionate monitoring approach should therefore be deliberately targeted. It does not need to replicate the full Phase 3 scientific programme. Instead, it should focus on indicators directly linked to the SPR model, attenuation performance, and management decision points. At minimum, this should include repeat $CH_4$ and $CO_2$ flux measurements at the known hotspot and immediate near-field area, basic soil-state observations to contextualise attenuation potential, and a visual receptor check for vegetation stress, drainage changes, land-use change, or new infrastructure.

Periodic monitoring outside peak summer oxidation conditions would be particularly valuable because winter or shoulder-season conditions may provide a more conservative test of attenuation performance. The purpose would not be to generate a new intensive research dataset, but to test whether the core assumptions of the appraisal remain valid when biological oxidation may be less favourable.

The recommended monitored management framework is summarised in Table 2.6.

**Table 2.6. Recommended monitored/management framework and escalation triggers for Wellsite J**

| Management element | Purpose | Proportionate approach | Escalation trigger |
|---|---|---|---|
| **$CH_4$ hotspot monitoring** | Track direct methane expression and source behaviour. | Repeat chamber flux measurements at the known hotspot and immediate near-field grid at reasonable frequency (e.g. yearly or bi-yearly). | Sustained increase in $CH_4$ flux magnitude, increased frequency of high-flux events, or expansion of the $CH_4$ hotspot beyond the established compact footprint. |
| **Paired $CH_4$–$CO_2$ monitoring** | Track attenuation expression and avoid $CH_4$-only interpretation. | Measure $CH_4$ and $CO_2$ together and interpret the $CH_4$:$CO_2$ relationship with soil temperature, moisture, and weather context. | Increasing $CH_4$:$CO_2$ ratio, weakening $CO_2$/oxidation signature, or evidence that $CH_4$ is increasingly bypassing the oxidation zone. |

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| **Seasonal / condition-aware reassessment** | Test whether attenuation remains effective outside favourable summer conditions. | Include occasional winter or shoulder-season monitoring where feasible. | Substantially higher winter/shoulder-season $CH_4$ expression, reduced oxidation performance, or a shift in the balance from $CO_2$-dominated attenuation expression to $CH_4$-dominated emission. |
| **Footprint stability check** | Confirm that leakage expression remains localised. | Repeat a small spatial flux grid around the known source area; targeted geophysical or geochemical checks only where needed to answer a management question. | Expansion of $CH_4$, $CO_2$, geophysical, or geochemical footprint beyond the established near-field zone. |
| **Shallow soil condition** | Track whether local soil perturbation remains limited. | Visual inspection and targeted soil/geochemical indicators where warranted. | Persistent vegetation stress, evidence of soil-function impairment, increasing geochemical alteration, or indications that the attenuation zone is becoming less effective. |
| **Groundwater / surface-water screening** | Retain conditional receptors without over-weighting them. | No routine intensive programme unless site evidence indicates a plausible connection. | Detection of dissolved methane, redox/geochemical change, drainage connection, or surface-water linkage attributable to the leakage system. |
| **Human/safety receptor review** | Ensure current low safety significance remains valid. | Reassess during land-use review or if infrastructure changes. | Introduction of enclosed structures, utilities, confined spaces, or occupied receptors near the leakage zone. |
| **Management review** | Prevent monitored management becoming passive deferral. | Maintain a short monitoring record and review against triggers after each monitoring round. | Any trigger exceedance, material change in site setting, or evidence that the Class 2 / low-to-moderate significance classification is no longer valid. |

If none of these escalation triggers are met, continued structured monitored management remains the most proportionate response. This would provide a defensible record that the site remains active but attenuated, that the shallow footprint remains localised, and that receptors remain protected. If one or more triggers are met, the management response should move to targeted investigation and, where warranted, targeted mitigation or active remediation planning.

The recommended decision logic is therefore:

**Current evidence supports structured monitored management. Escalate only if monitoring demonstrates increasing source strength, declining attenuation effectiveness, footprint expansion, or new receptor exposure.**

This decision logic avoids two problematic outcomes. It avoids under-management by recognising that a persistent fugitive gas source cannot be ignored. It also avoids over-management by recognising that not all confirmed legacy well leakage is environmentally equivalent. At Wellsite J, the evidence indicates a persistent but attenuated leakage system with modest atmospheric expression and localised shallow environmental impact. Under these conditions, structured monitored management is more proportionate than immediate intrusive remediation.

This conclusion should be revisited if future data indicate that the site is changing. The current appraisal is evidence-based but not permanent: it depends on continued low-to-moderate emissions, effective attenuation, a localised footprint, and limited receptor exposure. If those assumptions no longer hold, the management posture should be revised accordingly.