SATBAYEV UNIVERSITY

Engineering Journal of Satbayev University

Volume 148 (2026), Issue 2, 15-22

https://doi.org/10.51301/ejsu.2026.i2.03

Electromagnetic inter-well scanning (EIWS): scientific foundations, geological context, and applications in uranium in-situ leaching

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Abstract. Electromagnetic inter-well scanning (EIWS) is an advanced geophysical method that enables volumetric, time-resolved imaging of electrical conductivity within the inter-well domain of uranium in-situ leaching (ISL) systems. This article presents a comprehensive theoretical, geological, and methodological analysis of EIWS and evaluates its significance for monitoring reactive fluid transport in heterogeneous sandstone aquifers. The study highlights the method's sensitivity to salinity, porosity, permeability evolution, geochemical reactions, and acid front migration – key factors that govern ISL efficiency, breakthrough timing, and environmental containment. Through expanded discussion of electromagnetic physics, tomographic inversion, dynamic subsurface monitoring and operational optimization, EIWS is shown to be a transformative tool for characterizing subsurface processes that were previously inaccessible. The article concludes that EIWS fundamentally enhances recovery efficiency, improves sweep uniformity, strengthens environmental oversight, and establishes a new standard for scientific control of ISL operations.

Keywords: *electromagnetic inter-well scanning, uranium ISL, conductivity tomography, reactive transport, permeability heterogeneity, in-situ recovery monitoring.*

Received: 9 January 2026
Received in revised form: 6 April 2026
Accepted: 15 April 2026
Available online: 30 April 2026

1. Introduction

Uranium in-situ leaching (ISL), also known as in-situ recovery (ISR), has become the principal extraction technology for sandstone-hosted uranium deposits throughout the world. This transition has been driven not only by economic considerations but also by major environmental and operational benefits. Unlike traditional surface or underground mining, ISL does not require large excavations, waste rock removal, or tailings storage, and therefore minimizes ecological footprint, land disturbance, and long-term reclamation costs [1]. What makes the method especially attractive is the way it exploits the natural porosity and permeability of sedimentary aquifers, using them as dynamic reactors where uranium dissolution occurs directly within the geological formation. This allows the exploitation of deep, low-grade orebodies that would otherwise remain uneconomic under conventional mining technologies.

Despite these advantages, ISL has always faced a fundamental scientific challenge: the reactive transport processes that control uranium recovery occur in subsurface regions that operators cannot directly observe. The dissolution of uranium-bearing minerals, the movement of chemically reactive lixiviant solutions, the redistribution of groundwater, the formation of preferential flow channels, and the evolution of porosity and permeability take place in a three-dimensional space between injection and production wells. This inter-well region is the central arena of ISL, yet most traditional measurements and monitoring tools provide only indirect or incomplete information about it.

Borehole geophysical logging, although technologically advanced, is inherently limited to the immediate neighborhood of the wellbore. Resistivity, natural gamma, neutron porosity, density, induction, and spectral gamma logs provide valuable insights, but their depth of investigation typically does not exceed several tens of centimeters around the casing [2]. This small measurement volume represents only a tiny fraction of the overall region affected by leaching. Hydrodynamic tests such as pumping or slug tests provide transmissivity and storage parameters, but these are spatially averaged quantities that cannot resolve heterogeneity, channeling, or compartmentalization at the scale relevant to operational control [3]. Flow modeling, even in its most sophisticated forms, depends heavily on conceptual geological models that cannot be validated volumetrically. Tracer tests may confirm general hydraulic connectivity, yet they tend to overlook detailed internal structuring of the flow field, and their interpretation is complicated by retardation, adsorption, and dispersion [4].

Because of these limitations, ISL operations often remain partly empirical, relying on indirect indicators of sweep efficiency, breakthrough timing, and acid distribution. The lack of volumetric visibility in the inter-well space means that

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Engineering Journal of Satbayev University. eISSN 2959-2348. Published by Satbayev University

operators may not fully understand whether injected fluids are accessing targeted ore zones, bypassing stagnant volumes, or leaking vertically toward confining layers. This lack of insight translates into uncertainties in uranium recovery, acid losses, environmental risk, and the reliability of predictive reservoir models.

Electromagnetic inter-well scanning (EIWS) directly addresses this long-standing observational gap. The method is based on transmitting controlled electromagnetic waves from one borehole and recording their response in a second borehole. Because electromagnetic wave propagation is highly sensitive to the electrical conductivity of the medium, the amplitude and phase of arriving signals contain information about the conductivity distribution within the entire inter-well region [5]. Conductivity in porous media is strongly affected by pore-water salinity, acidity, ion mobility, and porosity – all of which evolve dynamically during ISL as chemical reactions proceed and permeability structures change. This makes EIWS not only a geophysical measurement but effectively a reactive transport monitoring tool, capable of revealing the geometry and evolution of fluid migration and geochemical alteration zones.

The result is a fundamentally new mode of reservoir observation. Instead of being limited to the borehole wall or relying solely on indirect tests, the operator gains access to volumetric, time-evolving images of the subsurface. EIWS can reveal preferential flow paths, stagnant pockets, erosion windows, bypassed ore zones, and geochemical fronts. It provides operational intelligence for adjusting wellfield hydraulics, optimizing injection strategies, and ensuring environmental containment. Finally, by offering time-lapse imaging, EIWS moves the ISL industry closer to the concept of a continuously monitored, dynamically optimized subsurface system.

2. Theoretical and methodological foundations of EIWS for uranium ISL

2.1 Geological heterogeneity and its role in reactive fluid transport

Understanding the geological framework of sandstone-hosted uranium deposits is essential for interpreting EIWS data and predicting how injected solutions will migrate through the reservoir. These deposits were formed in a variety of depositional environments: fluvial, deltaic, aeolian, and lacustrine and they exhibit heterogeneity at multiple scales. This heterogeneity is the defining characteristic controlling fluid transport, acid propagation, and overall leaching performance [6].

At the broader geological scale, uranium-bearing aquifers typically consist of stacked sandstone bodies interlayered with siltstones, clays, and paleosols. Their geometry reflects the dynamics of ancient river channels, floodplains, and deltaic distributary systems, resulting in a complex architecture of permeable and semi-permeable units. In fluvial systems, channel belts may contain coarse, well-sorted sands with high permeability, whereas overbank deposits may include fine-grained, low-permeability sediments. These architectural elements produce natural compartments that differ significantly in their hydraulic conductivity and transmissivity.

At the intermediate scale, variations in bedding, lamination, cementation, and diagenetic alteration impose additional controls on flow. For instance, thin clay drapes or ripple laminations may act as barriers to vertical fluid movement, causing acidized fluids to migrate laterally rather than vertically. Cross-bedded or inclined heterolithic strata may enhance anisotropy, promoting channelized flow along preferential lines while limiting access to adjacent volumes. The interplay between these sedimentary structures forms a hierarchical network of flow paths and baffles that is highly sensitive to chemical alteration.

At the micro-scale, pore-throat size distributions, grain contacts, diagenetic cements, and mineralogical variations determine pore connectivity and local reactivity. Carbonate dissolution plays a major role during acid leaching, increasing porosity and altering flow pathways [6]. Conversely, precipitation of secondary minerals, such as gypsum or silica, may locally reduce permeability. Since these reactions are spatially variable, the effective hydraulic structure of the reservoir continually evolves during ISL.

Reactive transport processes further complicate this geological setting. When sulfuric acid is injected, the first stage of reaction typically involves dissolution of carbonates and ferric minerals, releasing ions into the fluid phase and increasing conductivity. As the acid front moves, it may encounter zones rich in reactive minerals, which rapidly consume acid and buffer pH. In other areas, particularly those with limited permeability or restricted fluid access, the acid front may stall or bypass, leaving behind stagnant zones that retain uranium but do not meaningfully contribute to recovery [1].

Geological heterogeneity therefore produces highly uneven sweep patterns. Fluvial channel sands may become heavily acidized, showing increased conductivity detectable by EIWS, while adjacent siltstone lenses remain unperturbed. Erosion windows may permit uncontrolled fluid communication between stratigraphic levels, introducing environmental and operational risks. In contrast, subtle clay-rich barriers may protect deeper or adjacent zones from acid invasion, preserving their natural state.

Because conductivity responds strongly to both lithological and geochemical differences, EIWS provides a means of capturing these complex interactions within the inter-well space. Conductive anomalies often correlate with acid-invaded zones, high-salinity pockets, or dissolution-enhanced pathways. Resistive anomalies typically indicate unreacted ore, clay-rich barriers, or isolated regions that fail to participate in flow. Over time, as the acid front migrates and the reservoir evolves, EIWS can track these changes, revealing dynamic patterns that reflect the combined influence of geology, hydrodynamics, and geochemistry.

In summary, the geological heterogeneity of ISL deposits is not merely a static background but an active participant in the leaching process. It shapes the geometry of flow, controls the distribution of reactive phases, and ultimately governs the efficiency of uranium extraction. EIWS, by imaging conductivity changes arising from these processes, offers a window into the inner workings of the reservoir, allowing operators to move beyond empirical approaches and toward scientifically grounded optimization of ISL operations.

2.2 Physical principles of electromagnetic inter-well scanning

Electromagnetic inter-well scanning (EIWS) is grounded in the classical physics of electromagnetic wave propagation in conductive, porous, fluid-saturated geological media. The fundamental basis of the method rests on Maxwell's equations, which together describe how time-varying electric and magnetic fields interact with materials that possess conductivity, permittivity, and permeability. Although the theory is well established, its application within chemically reactive environments such as uranium ISL presents a complex interplay between physics, geology, fluid chemistry, and evolving rock properties. The subsurface conditions shaped by in-situ leaching provide a highly dynamic electromagnetic medium, whose properties change over time as dissolution and precipitation processes modify pore networks, fluid composition, and ion mobility.

In a conductive geological medium, electromagnetic field propagate in a diffusive rather than wave-like manner. This means that instead of traveling as well-defined waves, the electromagnetic energy penetrates the formation with exponential attenuation governed primarily by the electrical conductivity of the medium. The relevant expression controlling penetration depth is the skin depth, which is inversely proportional to the square root of conductivity and frequency. High conductivity, as commonly found in acidized or highly saline zones, leads to rapid attenuation. This sensitivity is precisely what makes EIWS valuable in ISL settings acidized zones are strongly conductive and therefore produce measurable changes in amplitude and phase between transmitter and receiver.

The relationship between electrical conductivity and subsurface conditions is complex but highly advantageous for monitoring ISL. Conductivity increases significantly when sulfuric acid dissolves carbonates and sulfates [7], releasing ions such as Ca^{2+}, Mg^{2+}, SO_4^{2-}, and H^+ into the pore fluid. These ions enhance the fluid's ability to carry electric current, producing sharp contrasts relative to less impacted regions. As the leaching front advances, these chemical transformations modify not only fluid conductivity but also the mineral structure, pore geometry, and microfracture network. Zones experiencing active dissolution tend to become more conductive due to increased ionic strength and improved pore connectivity. In contrast, areas undergoing secondary mineral precipitation, such as gypsum formation, may exhibit reduced conductivity or complex mixed responses. EIWS is sensitive to all of these processes.

The operational configuration of EIWS involves deploying a controlled electromagnetic transmitter in one well and a sensitive receiver in another well spaced typically between 20 and 80 meters away. The transmitter emits electromagnetic waves over a range of frequencies [8,9]. Lower frequencies penetrate more deeply into the formation and sample the entire inter-well region, while higher frequencies provide finer discrimination of shallow or localized features. The receiver measures both amplitude and phase shift, which encode information about the medium through which the waves have passed. Unlike borehole logs that measure properties immediately adjacent to the borehole wall, EIWS captures volumetric information, integrating responses across the entire inter-well trajectory.

The interpretation of EIWS measurements depends heavily on solving a nonlinear inverse problem. Electromagnetic wave propagation in a conductive medium is governed by partial differential equations that must be numerically approximated. Forward modeling predicts the electromagnetic response for a hypothetical conductivity distribution. The inverse problem seeks to find the conductivity distribution that best explains the observed data. However, this inversion is inherently ill-posed: many possible conductivity models can produce similar electromagnetic responses, especially when data are noisy or incomplete. Therefore, robust regularization techniques are required to stabilize the inversion. Modern EM inversion approaches incorporate constraints such as smoothness, spatial coherence, and prior geological knowledge to produce geologically plausible models [10-12].

Regularization strategies, such as Tikhonov regularization or model-weighted smoothing, are essential in preventing nonphysical oscillations. Recent developments also include the use of geostatistical priors, Bayesian inversion frameworks, and machine-learning-enhanced inversion methods. Numerical modeling studies of electromagnetic wave propagation in heterogeneous aquifers have shown that sensitivity is highest along direct transmitter–receiver paths but remains significant in off-path regions, meaning that EIWS can effectively map zones not directly aligned with the inter-well axis. This makes EIWS particularly suitable for complex geological formations where flow pathways may diverge significantly from the direct line connecting two wells.

In an ISL environment, the physical interpretation of EIWS can be enhanced by integrating chemical and hydrological understanding. For example, at the early stages of acid injection, conductivity increases sharply at the leading edge of the acidic plume. This creates a fast-moving, conductive front often detectable as a pronounced anomaly in EIWS. As leaching continues, conductivity may evolve due to mineral dissolution, partial neutralization of acid, and changes in salinity. Toward the end of the leaching cycle, when the formation is rinsed, conductivity anomalies may diminish or change shape, providing a diagnostic indicator of the effectiveness of rinsing or the extent of residual acidic zones.

The dynamic nature of electromagnetic properties under ISL conditions implies that EIWS can serve not merely as a static imaging tool but also as a temporal monitoring system. Time-lapse measurements allow operators to observe the evolution of subsurface conductivity fields, track acid front movement, and detect changes in permeability or flow patterns. When EIWS data are collected at regular intervals, they form a temporal sequence that can be used to reconstruct the four-dimensional behavior of the reservoir. This makes EIWS one of the few technologies capable of delivering real-time, volumetric assessment of subsurface reactive transport.

Another factor influencing EIWS responses is the presence of anisotropy in geological formations. Many sedimentary aquifers exhibit anisotropic conductivity due to bedding planes, lamination, or preferential orientations of clay minerals. Anisotropy affects electromagnetic wave propagation differently depending on field orientation, thus making inversion more complex. Advanced EIWS implementations can incorporate tri-axial transmitter and receiver systems to better resolve anisotropy and improve tomographic accuracy.

Finally, while metallic casings commonly found in ISL wells can distort electromagnetic fields, modern EIWS systems incorporate sophisticated calibration procedures and casing compensation algorithms. These developments allow the method to be used effectively even in fully cased production wells, which is a major advantage over some forms of geophysical logging that require open holes or special well completions.

Overall, the physical principles of EIWS reflect a rich interplay between electromagnetic theory, subsurface geology, fluid chemistry, and reactive transport processes. It is this combination of sensitivity to chemical changes, compatibility with cased wells and volumetric coverage that makes EIWS uniquely suited for ISL monitoring. The method moves beyond traditional geophysical tools by providing actionable, physically grounded insights into the evolving conditions within the inter-well region, where the critical processes of uranium leaching are most actively occurring.

3. Results and discussion

3.1 Dynamic monitoring of ISL processes and practical significance

One of the most powerful aspects of electromagnetic inter-well scanning is its ability to monitor reactive fluid movement and geochemical transformations dynamically throughout the operational life of an in-situ leaching (ISL) wellfield. While traditional geophysical logs and hydrogeological measurements capture only static snapshots or indirect indicators of the subsurface, EIWS offers a fundamentally different perspective - one that evolves over time and reflects the continuous progression of the leaching system as it moves through distinct operational stages. In this sense, EIWS is not merely a diagnostic tool but a framework for adaptive management, enabling timely decisions driven by real-time information about how injected fluids are distributed, how the ore is being accessed, and where inefficiencies or risks may be emerging.

From the very beginning of ISL operations, EIWS provides actionable insights. During the initial acid push phase, the foremost priority is to understand whether the injected lixiviant is penetrating the intended ore-bearing intervals and whether it is doing so evenly across the inter-well region. Early EIWS surveys typically reveal the initial geometry of acid invasion. Highly conductive anomalies tend to form rapidly where permeability is greatest, often highlighting pre-existing geological features such as paleo-channels, permeable layering, or localized microfracture networks. These early observations serve as a «first look» into the functional connectivity of the reservoir, identifying channels that will dominate flow as operations progress.

As injection continues, time-lapse EIWS begins to reveal the dynamics of the acid front. In an idealized scenario, the front advances smoothly and symmetrically through the inter-well region, ensuring a large contacted volume and high sweep efficiency. However, actual field conditions rarely conform to this ideal. Geological heterogeneity, variable permeability, anisotropy, and subtle structural controls frequently distort the shape of the reaction front. EIWS can detect these distortions with sufficient clarity to allow meaningful operational adjustments. If the acid front is advancing too rapidly along a high-permeability corridor, the increasing conductivity will highlight this «fast path», enabling operators to reduce injection in certain wells, reallocate flow, or temporarily shut in areas that are advancing too quickly.

At the same time, EIWS can identify zones of poor fluid access. These appear as persistently resistive regions between wells, often indicating stagnant pockets that remain uncontacted by the acid front. Such stagnant zones are operationally significant because they frequently contain uranium that remains unrecovered even after extensive leaching. They also represent areas where the chemical environment may remain reducing, buffering the advance of acid and slowing the kinetics of dissolution. Once identified, these stagnant volumes can be targeted with specific engineering measures, such as modifying injection depths, stimulating flow pathways, or implementing alternating injection–extraction regimes to redistribute pressure gradients.

As the leaching cycle progresses into the mid-stage, the relationship between conductivity and reactive transport becomes more complex. Conductivity may continue increasing in areas where continued dissolution mobilizes ions, but other zones may transition toward mixed or even decreasing conductivity if secondary mineral precipitation occurs or if acid is consumed faster than it is replenished. These subtle patterns are invaluable for understanding the underlying reaction mechanisms. For example, a localized decline in conductivity during the mid-stage may indicate gypsum precipitation or partial clogging of pore throats, reducing permeability and altering flow patterns. Such emergent behaviors are nearly impossible to detect without volumetric monitoring such as EIWS.

The dynamic capability of EIWS becomes even more valuable as operators move toward later stages of leaching, where production volumes begin to decline and breakthrough events start to dominate. Breakthrough, when injected acid preferentially reaches production wells through highly permeable channels, can drastically reduce sweep efficiency and increase chemical losses. EIWS provides a means to detect early signs of breakthrough by imaging increasingly conductive zones that begin to form near production wells. When these anomalies appear, operators can redistribute injection away from problematic wells or introduce balancing injections in other parts of the wellfield to mitigate the effects of channeling.

The ability to detect vertical or lateral migration beyond the intended extraction zone is another critical function of EIWS monitoring. While ISL relies on the presence of confining layers to restrict vertical fluid movement, weak points such as erosion windows, poorly cemented intervals, or subtle fractures may permit cross-formational communication. Conductive anomalies appearing above or below the ore zone in EIWS data can indicate such breaches [13,14]. Early detection is essential, as excursion events represent both environmental risks and regulatory compliance issues. EIWS provides operators with the sensitivity needed to identify these migration patterns long before conventional groundwater sampling or hydraulic monitoring would detect them.

In the final stages of ISL operations, as the wellfield transitions to rinse and restoration, EIWS plays a unique role in evaluating the effectiveness of flushing operations. Residual acid, elevated salinity, and persistent conductive anomalies may indicate zones where restoring groundwater quality will be challenging [15-18]. These anomalies help identify areas that require targeted hydraulic isolation or extended rinsing. Because restoration is often the most time- and cost-intensive part of ISL operations, the ability to map residual conductive zones helps operators optimize restoration strategies and avoid unnecessary effort in areas already stabilized.

From an economic perspective, the operational significance of EIWS cannot be overstated. By improving sweep efficiency, reducing acid losses, mitigating breakthrough risks, enhancing uranium recovery, and ensuring more efficient rinsing, EIWS enables substantial cost savings.

Operational improvement is only one dimension of EIWS's importance; environmental protection is another. Because EIWS can detect the migration of conductive fluids beyond the wellfield boundaries or outside the intended stratigraphic interval, it helps prevent and control environmental excursions. By providing early detection of leakage, EIWS enables operators to respond before excursions become serious or regulatory thresholds are exceeded. This capability aligns with modern environmental governance frameworks, which increasingly require real-time or near-real-time monitoring of subsurface processes to ensure safe operation.

On a broader conceptual level, EIWS contributes to a shift in the philosophy of subsurface resource management. Historically, ISL operations have relied heavily on indirect inference; now, with EIWS, operators gain a capacity for direct observation of subsurface reactive transport processes. This transition mirrors other advances in earth science, such as the adoption of time-lapse seismic monitoring in hydrocarbon reservoirs. In many ways, EIWS represents a similar leap forward for the uranium industry, creating the basis for a more predictive, more controllable, and more scientifically grounded operational paradigm.

In summary, the dynamic monitoring capabilities of EIWS make it an essential tool for modern ISL operations. Its ability to visualize the evolution of the reservoir, detect operational issues before they become problematic, guide real-time decision-making, and improve both economic and environmental performance establishes EIWS as a cornerstone technology for the future of uranium in-situ leaching.

3.2 Limitations, uncertainties, and methodological challenges

Despite the clear advantages and transformative potential of Electromagnetic inter-well scanning, the method is subject to a variety of limitations and uncertainties that must be carefully understood when applying it to the complex subsurface environments encountered in uranium ISL operations. These limitations arise from both fundamental physical constraints and practical operational considerations. Recognizing them allows practitioners to correctly interpret tomographic images, integrate EIWS data with other datasets, and ultimately improve the reliability of reservoir evaluations.

One of the primary challenges arises from the diffusive nature of electromagnetic propagation in conductive geological media. When conductivity is high, as it often is in acidized, saline, or clay-rich formations, electromagnetic waves experience rapid attenuation. This reduces depth of investigation, creates blind zones in high-conductivity strata, and limits the ability to resolve fine-scale features. In certain ISL environments, particularly those with thick layers of conductive clays or shales, the penetration depth of higher-frequency signals may be severely constrained. Lower frequencies can mitigate this issue, but at the cost of reduced spatial resolution. Thus, EIWS must balance frequency selection with geological characteristics to maximize effectiveness.

Another significant limitation concerns anisotropy in sedimentary formations. Many uranium-bearing sandstone aquifers exhibit pronounced anisotropy resulting from bedding planes, lamination, preferential alignment of clay minerals, or depositional features such as cross-bedding. Anisotropy affects how electromagnetic waves propagate, sometimes allowing preferential propagation along certain directions while attenuating waves in others. If anisotropy is not incorporated into the inversion algorithm, tomographic images may misrepresent the geometry or magnitude of conductivity features. Although advanced inversion techniques allow anisotropy to be modeled, such approaches require additional data and computational complexity.

Equally important are the effects of well casing, particularly metallic casing, which is standard in most ISL wells. Metal casing produces eddy currents [19] that distort the electromagnetic field, alter amplitude and phase measurements, and reduce signal sensitivity to the surrounding formation. These distortions must be corrected through calibration procedures, casing compensation algorithms, and careful tool design. While modern EIWS systems are capable of operating effectively in cased wells, the presence of casing still reduces sensitivity relative to open-hole environments and imposes practical constraints on tool orientation and frequency usage.

A further methodological challenge arises from the inherent non-uniqueness of the electromagnetic inverse problem. Since many conductivity distributions can produce similar electromagnetic responses, the inversion process relies heavily on regularization to select a stable and geologically plausible model. However, strong regularization inevitably smooths the resulting tomograms and may obscure fine-scale heterogeneities. Conversely, insufficient regularization may allow noise or numerical artifacts to dominate the solution. Achieving the correct balance is nontrivial and requires substantial expertise in inversion theory, numerical modeling, and reservoir geology.

Additionally, EIWS inversion is sensitive to measurement noise, which can originate from electronics, external electromagnetic interference, variable borehole conditions, and environmental factors. Noisy data can lead to instabilities in inversion, particularly in low-sensitivity regions or where wave attenuation is high. Data preprocessing, filtering, and careful acquisition protocols are therefore essential components of reliable EIWS practice.

Beyond these physical and computational challenges, there are broader uncertainties connected with reservoir complexity and incomplete geological knowledge. In many ISL fields, detailed core data may be sparse, spatially uneven, or unavailable, forcing reliance on log-based geological interpretations that may not fully capture the true heterogeneity of the system. When prior geological information is inaccurate or oversimplified, inversion algorithms may impose biases, leading to misinterpretation of conductive and resistive anomalies. Integrating EIWS with lithological, hydrodynamic, and tracer data helps reduce such risks by anchoring inversion results in multiple lines of evidence.

Another difficulty concerns multi-physics coupling. The electrical conductivity measured by EIWS reflects the combined effects of lithology, salinity, porosity, acidity, and temperature. These factors may evolve simultaneously but not linearly. For example, conductivity may increase during acidization due to increased salinity but decrease later if permeability is lost due to secondary mineral precipitation. Distinguishing between chemical and hydrological drivers of conductivity anomalies requires careful interpretation and cross-disciplinary knowledge. In some cases, calibration with laboratory measurement of conductivity–porosity–salinity relationships may be required.

Finally, EIWS faces practical limitations in spatial coverage. Although the method provides volumetric imaging between pairs of wells, full coverage of an ISL wellfield requires multiple scanning configurations. In large wellfields with dozens or hundreds of wells, achieving complete coverage may be time-consuming or logistically challenging. Prioritization strategies, where EIWS surveys focus on areas of greatest operational uncertainty, can ease this burden while still providing valuable insights.

In spite of these limitations, EIWS remains one of the most informative and adaptable monitoring techniques available for ISL operations. Many of the challenges can be mitigated through improved acquisition design, integration with other datasets, advanced inversion methods, and ongoing refinement of geological models. Indeed, as EIWS technology continues to evolve, the scope and reliability of its applications are expected to expand significantly.

4. Conclusions

Electromagnetic inter-well scanning represents a fundamental advancement in the monitoring, interpretation, and control of uranium in-situ leaching systems. In contrast to traditional geophysical and hydrological techniques, which offer only partial, indirect, or near-borehole insights, EIWS enables volumetric imaging of the inter-well region the very domain where leaching reactions occur, where permeability architecture governs flow, and where operational performance is ultimately determined. The method provides unprecedented visibility into the subsurface, revealing how injected solutions move through heterogenous sandstone aquifers, how geochemical fronts evolve, and how permeability structures transform as reactive processes unfold.

The expanded analysis presented in this manuscript demonstrates that EIWS is more than an incremental improvement in subsurface monitoring; it is a paradigm shift. By leveraging the sensitivity of electromagnetic fields to fluid chemistry, porosity, and geochemical alterations, EIWS offers a means of directly observing the dynamic behavior of the reservoir. Conductive anomalies highlight preferential flow channels, breakthrough pathways, and acidized zones, while resistive anomalies illuminate stagnant pockets, lithological barriers, and regions of limited hydraulic connectivity. These insights empower operators to identify inefficiencies early, adjust wellfield hydraulics in real time, and ensure that the leaching system performs as intended.

The geological heterogeneity characteristic of sandstone-hosted roll-front uranium deposits further increases the importance of such imaging. These reservoirs exhibit a complex hierarchical structure, ranging from grain-scale porosity variations to large-scale channel systems, all of which influence the transport of reactive solutions. EIWS enables practitioners to capture the cumulative effects of this heterogeneity. It makes possible a more nuanced understanding of why some regions of the reservoir leach efficiently while others remain under-reacted, why breakthrough occurs prematurely in certain wells, and how hydraulic connectivity evolves in response to chemical transformations.

In addition to its operational benefits, EIWS enhances environmental assurance. Uranium ISL requires strict containment of reactive solutions within designated aquifer boundaries, and EIWS provides the sensitivity and spatial resolution necessary to detect vertical or lateral migration before it becomes significant. By identifying unanticipated conductive anomalies outside the production horizon, EIWS enables early intervention and reduces the risk of excursions into surrounding groundwater systems. This capability will only grow in importance as the regulatory landscape tightens and environmental standards become more stringent.

Author contributions

Conceptualization: BVT; Data curation: BVT; Formal analysis: BVT; Funding acquisition: BVT; Investigation: BVT; Methodology: AAB; Project administration: AAB; Resources: BVT; Software: BT; Supervision: AAB; Validation: BVT; Visualization: BVT; Writing – original draft: BVT; Writing – review & editing: AAB. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgements

The authors express their sincere gratitude to the editor and anonymous reviewers for their constructive comments and valuable suggestions, which have significantly improved the quality of this manuscript.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Электромагниттік ұңғымааралық сканерлеу (ЭҰС): ғылыми негіздері, геологиялық контексті және уран жер асты шаймалау кезіндегі қолданылуы

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Аңдатпа. Электромагниттік ұңғымааралық сканерлеу (ЭҰС) ұңғымааралық кеңістіктің электр өткізгіштігінің көлемдік картасын қамтамасыз етеді және уранды жер асты ұңғымалы шаймалау (ЖҰШ) тиімділігін анықтайтын геологиялық факторларды тікелей бағалауға мүмкіндік береді. Құмтас коллекторларының литологиялық және құрылымдық гетерогенділігі-гранулометрияның өзгергіштігі, қабаттылық, саз қабаттары, өткізгіштік анизотропиясы, диагенетикалық түрлендірулер және жергілікті тектоникалық бұзылулар кәріз ағындарының, сүзу қиын аймақтардың және сілтілеу процесіне кенді интервалдардың қатысу деңгейінің қалыптасуын бақылайды. ЭҰС осы контрасттарға жоғары сезімталдыққа ие және реагенттердің кеңістіктік таралуын бекітеді, бұл тосқауыл горизонттарын, тоқырау аймақтарын және қышқыл майданының жеделдетілген ілгерілеу учаскелерін анықтауға мүмкіндік береді. Уақытша томограммалар геохимиялық өзгерістердің динамикасын көрсетеді және геологиялық құрылым, гидродинамикалық процестер мен уранның алынуы арасындағы байланысты ашады. ЭҰС деректерін геологиялық модельдеумен және стратиграфиялық құрылымдармен интеграциялау қабаттың жай-күйін бағалаудың дәлірек тәсілін қалыптастырады, ұңғымалар торын оңтайландыруға, қамтудың біркелкілігін арттыруға және экологиялық қауіпсіз пайдалануды қамтамасыз етуге мүмкіндік береді.

Негізгі сөздер: *электромагниттік ұңғымааралық сканерлеу, геологиялық әртектілік, стратификацияланған құмтастар, өткізгіштік анизотропиясы, уран ЖҰШ.*

Электромагнитное межскважинное сканирование (ЭМС): научные основы, геологический контекст и применение при подземном выщелачивании урана

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Аннотация. Электромагнитное межскважинное сканирование (ЭМС) обеспечивает объёмное отображение электрической проводимости межскважинного пространства и позволяет напрямую оценить геологические факторы, определяющие эффективность подземного скважинного выщелачивания урана (ПСВ). Литологическая и структурная неоднородность песчаниковых коллекторов — изменчивость гранулометрии, слоистость, глинистые прослои, анизотропия проницаемости, диагенетические преобразования и локальные тектонические нарушения контролируют формирование канализированных потоков, зон затруднённой фильтрации и уровня вовлечённости рудных интервалов в процесс выщелачивания. ЭМС обладает высокой чувствительностью к этим контрастам и фиксирует пространственное распределение реагентов, что позволяет выявлять барьерные горизонты, застойные зоны и участки ускоренного продвижения кислотного фронта. Временные томограммы отображают динамику геохимических изменений и раскрывают взаимосвязь между геологическим строением, гидродинамическими процессами и извлекаемостью урана. Интеграция данных ЭМС с геологическим моделированием и стратиграфическими построениями формирует более точный подход к оценке состояния пласта, позволяет оптимизировать сетку скважин, повысить равномерность охвата и обеспечить экологически безопасную эксплуатацию.

Ключевые слова: *электромагнитное межскважинное сканирование, геологическая неоднородность, стратифицированные песчаники, анизотропия проницаемости, ПСВ урана.*

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