Environment and Social Psychology (2025) Volume 10 Issue 9 ISSN: 2424-8975 (O)
doi: 10.59429/esp.v10i9.3956 2424-7979 (P)

RESEARCH ARTICLE

Legal implications of utilizing geophysical methods for resource exploration and environmental protection

Mohammed Zuhair[1], Ameen Hadi Hassoon Ali[2], Israa Zaidan Khalaf Mashhoot[3], Bushra Abd-Al Latif Jasim[4], Ghanim Magbol Alwan[5*]

[1] *Al-Turath University, Baghdad 10013, Iraq*

[2] *Al-Mansour University College, Baghdad 10067, Iraq*

[3] *Al-Mamoon University College, Baghdad 10012, Iraq*

[4] *Al-Rafidain University College, Baghdad 10064, Iraq*

[5] *Madenat Alelem University College, Baghdad 10006, Iraq*

*** Corresponding author:** Ghanim Magbol Alwan, dr.ghanim.m.alwan@mauc.edu.iq

ABSTRACT

Geophysical techniques have emerged as indispensable tools in the field of resource exploration and environmental monitoring, providing key benefits in subsurface imaging, non-destructive surveying, and analytical decision support. But their deep adoption has also raised fundamental legal questions about regulatory clarity, environmental accountability, stakeholder rights and data reliability. We discuss legal frameworks governing geophysical techniques in a range of jurisdictions, evaluating how these frameworks balance environmental management, procedural efficiency and party equity. Through a multidisciplinary procedure, this study integrates legal evaluation, environmental impact models, stakeholder survey information, comparative jurisdictional evaluation, and geophysical data verification. Results show significant differences in the clarity and enforcement of the law between countries, with some jurisdictions having efficient and aligned regulation and others with an excessive level of red tape. (Stakeholder sentiment suggests perceptions of legal fairness are mixed at best, with landowners expressing the greatest dissatisfaction, especially in the transparency and compensation mechanisms.) Additionally, despite the relatively low-impact nature of the surveys, many measurable disturbances, particularly increased noise and vibration, suggest the need for increased environmental oversight. The analysis also highlights the critical importance of checking geophysical datasets to maintain a scientific standard in regulatory or legal contexts. The conclusion of this study highlights the need for legal evolution to keep pace with technological evolution, through clearer rules, standards harmonization and data quality protocols. This requires amendments to regulations to enable responsible exploration, promote environmental sustainability, and ensure equitable stakeholder engagement in the governance of geophysical activities.

Keywords: Geophysical methods; environmental regulation; legal frameworks; resource exploration; stakeholder rights; regulatory complexity; data integrity

ARTICLE INFO
Received: 29 July 2025 | Accepted: 30 September 2025 | Available online: x October 2025

CITATION
Zuhair M, Ali A H H, Mashhoot I Z K. Legal Implications of Utilizing Geophysical Methods for Resource Exploration and Environmental Protection. *Environment and Social Psychology* 2025; 10(9): 3956. doi:10.59429/esp.v10i9.3956

1. Introduction

In the modern age the interdependence between resource exploration and environment protection is increasing. As societies are faced with the growing challenge of satisfying the demands of energy, minerals and other natural resources; these demands must be balanced by the societal need to build and maintain a sustainable environmental balance. In this scenario, geophysical techniques became indispensable tools for exploring and extracting underground resources. Seismic imaging, ground-penetrating radar, and magnetotellurics can be used to map underground structures, detect mineral deposits, and track aquifer systems. These techniques can deliver important data to support responsible extraction, lower environmental disruption and improve exploration operations efficiency [1].

However, the widespread application of geophysical methods gives rise to a complex spectrum of legal issues. Geophysical techniques can thus transcend ownership boundaries and impact multiple stakeholders, unlike traditional resource exploration practices that were confined to surface surveys and direct drilling. For instance, seismic surveys on one tract of land could unintentionally result in data about adjacent properties. This creates questions such as data ownership, landholder rights, and whether or not operators can enter private land in certain situations. In addition, the evolution of these technologies raises frustrating challenges for established bodies of law, which, at least as yet, can hardly be expected to provide an account of their unique operational and environmental characteristics [2].

A related dimension is geophysical ways to affect the environment sensitive areas. Seismic vibrations or electromagnetic emissions, for example, can displace wildlife in habitats where they are flourishing or change groundwater flow patterns or otherwise cascade in ways that have unintended effects in protected regions. The legal system will have to wrestle with the question of how much operators have to do to blunt these effects, and the punishment for failure to do so. Moreover, geophysical data is usually processed with sophisticated techniques, leading to further questions of privacy, security, and intellectual property. What kind of legal problems does the use of proprietary algorithms and datasets to generalize subsurface conditions across wide geographic areas create? These aspects give rise to an urgent demand for a solid legal framework that is good at adapting to the continuously changing technological advancements and the evolving social values [3].

This intersection of law and geophysical methods occurs on the international level as well. With resource exploration developing into more globalized markets, multinational companies are faced with a patchwork of national regulations, regional pacts and international treaties. This adds complexity that the natural environment often does not conform to, leading to conflicts between jurisdictional areas with different environmental standards and different applications of values placed or regulations applied to geophysical data. Now more than ever the world needs harmonized legal principles that balance cross-border collaboration with the need for environmental safeguards. And meanwhile, local communities and indigenous groups are demanding a seat at the table for the decision-making process and trying to get their rights and interests recognized in the law. This multilayered character of legal issues regarding geophysical applications and resource searching is reinforced by these dynamics [4].

Within this fluid landscape, the attorneys facing increasingly critical questions: How can laws catch up with the new technology underlying geophysical exploration? What mechanisms are necessary to make sure that measures to protect the environment are not undermined in the pursuit of natural resources? What could be the role of legal instruments to promote transparency, accountability and fair access to subsurface data? To engage with these questions, we need both a retrospective analysis of existing legal frameworks and a prospective outlook for policymaking [5].

The legal questions presented if geophysical methods are used in resource exploration and environmental protection are discussed. This article provides insights into the ways that law both enables and constrains geophysical practices by analysing the current legal frameworks, identifying gaps in regulation, and suggesting avenues for reform. This article aims to elucidate the legal dimensions of geophysical exploration through an analysis of relevant case studies, statutory frameworks, and associated case law. It must be underscored those policies are established balancing economic growth, resources exploration, environmental responsibility, and all parties' right.

1.1. The aim of the article

This article aims to explore the various legal risks associated with the use of geophysical techniques in resource exploitation and environmental conservation. With advancements in technology enabling new methods to undertake natural resource exploration and monitoring, the next step is considering what emerging legal instruments could govern such activities. The purpose is to offer a detailed overview of existing legal frameworks and the strengths, weaknesses, and gaps within them. Instead, the article aims to provide practical suggestions on how legal and regulatory frameworks could adapt to better recognize the distinctive attributes of geophysical surveying methods.

A major theme of this article #notes is to examine the impact of geophysical methods on property rights, data ownership, and land access. It aims to clarify the legal obligations of operators whose advanced imaging technologies work their way outside of more traditional physical and regulatory boundaries. Another goal is to examine how environmental regulations can help to avoid the possibility that geophysical activities could adversely affect sensitive ecosystems or undermine longer-term goals for sustainable development. Through an examination of existing statutes, case law, and international agreements, this article seeks to promote consideration of where regulatory frameworks may be lacking or slow to respond to new technologies.

Potential legal considerations when operating across jurisdictions, and the increasing need for legal certainty in cross-jurisdictional arrangements. As geophysical methods are employed in multinational operations, it is essential that the legal standards are harmonized and that all parties involved—be they governments, companies, or local communities—understand their rights and responsibilities. Thus, in this respect, the article aims to help advance legal principles that promote transparency, accountability, and fair and equitable management of resources.

1.2. Problem statement

The use of geophysical methods for resource exploration and environmental remediation has further given rise to a myriad of legal and regulatory issues, which have not been exhaustively addressed by existing models. These developments have not merely facilitated more efficient oil and gas generation; they have also transformed the field of exploration geoscience, where traditional techniques such as seismic imaging, electromagnetic surveys, and ground-penetrating radar are used to enhance the identification and assessment of subsurface resources. But these technologies are often situated at the intersection of multiple areas of law, such as property rights, environmental law, and data governance. The absence of a uniform regulatory framework had enabled numerous critical problems.

The issue of property and of access rights on that property is particularly fraught. Geophysical methods often capture data beyond operation area, thereby trespassing illegally neighbor landowners rights. The lack of definitional clarity on who owns land, and who owns the data collected on that land, makes it difficult to indicate responsibility and liability [6]. Here, landowners and operators of the resources may dispute the permissibility of the data acquisition techniques used, the proprietary rights to the information collected, and the due allocation of benefits from resource discoveries.

Environmental issues further complicate the legal uncertainty. Although geophysical methods provide a less invasive approach to resources assessment, they can also cause indirect environmental damage; such as habitat deformation and groundwater flow alteration. In particular, existing environment regulation that is often outdated or ill-fitted has left gaps in accountability and enforcement mechanisms.

The international character of resource exploration makes the problem a global one. Laws in different jurisdictions impose different legal standards, leading to inconsistencies and hindrances to cross-border collaboration. Without uniform principles of law, operators will have to manage inconsistent rules, and communities will be unevenly treated vis-a-vis land use and environmental protection.

However, the most significant problem we face is poor/fragmented legal frameworks in all stages of how geophysical methods are used. We must tackle these challenges if we are to promote responsible exploration for resources and ensure that rights are fairly allocated and environmental integrity protected.

2. Literature review

Increasing use of geophysical methods in resource exploration and environmental monitoring has generated diverse views regarding their legal and regulatory implications. In terms of the current academic discourse, a good part is based on the technical capability of geophysical techniques (such as seismic surveys, electromagnetic imaging, ground-penetrating radar) and their ability to provide detailed data subsurface. These studies highlight the transformative impact of such technologies in locating mineral deposits, assessing groundwater reserves, and monitoring environmental conditions. This corpus of work is, however, still immature; the legal architectures around their utilization receive limited attention, often tied down to specific jurisdictions or case studies. Consequently, there is a vast gap in addressing how laws can be adapted to suit the distinct challenges of geophysical exploration [7].

This is a common theme in the literature: the need for innovative resource assessment methods is always somewhat at odds with a legal system that was built and is largely operated, based on the best technology of the time in which it developed. Although plenty of scholars have acknowledged the usefulness of non-invasive geophysical tools, with excitement around things like less ground disturbance and better data, there has been hot debate as to how these benefits are balanced against concerns regarding land access and data ownership, as well as environmental concerns[8]. For instance, it has been noted that existing legal frameworks do not sufficiently account for the geophysical data that is collected, particularly when it takes the form of geophysical data flows that traverse property boundaries or impact multiple interests. This has prompted calls for a more unified and comprehensive regulatory framework which balances technological progress with social and environmental concerns [9].

Moreover, recent scholarship has underscored that the regulatory challenges tied to geophysical exploration cannot be examined in isolation from broader environmental and geo-ethical discourses. For example, the expansion of geo-ethics highlights the importance of linking technical practices with community perceptions and place-based environmental responsibilities [3]. Comparative perspectives from international law further demonstrate how integrated frameworks—such as the Water-Energy-Food nexus in the Arctic—offer lessons for aligning fragmented regulations across sectors [4]. At the same time, empirical studies of compliance, such as the assessment of criminal environmental law in Kosovo, reveal that legal fragmentation persists even when supranational directives mandate harmonization [10]. These insights suggest that regulatory reform for geophysical methods must not only address technical clarity but also incorporate interdisciplinary models that account for governance complexity, stakeholder rights, and environmental justice.

Exploration of another important aspect concerning geophysical methods in ecologically sensitive areas. There are several authors who have discussed how these technologies can reduce ecological disruption and aid in more sustainable use of resources. Simultaneously, there is increasing awareness that traditional environmental regulation may not adequately capture the indirect impacts of geophysical activity, for example, from noise pollution, changes in the flow of subsurface water, or long-term shifts in ecosystems. This has prompted ongoing debates about how environmental laws can be revised to account for the capabilities and limitations of contemporary geophysical methods [11].

Aside from these tangible ecological issues, the papers also show the growing concern towards the international law aspects of geophysical exploration. With resource extraction growing increasingly globalized, the need for harmonized legal standards and cross-jurisdictional cooperation is gaining traction. Scholars have examined how the variances in regulatory frameworks throughout countries can lead to inconsistencies, complicating the management of projects, and contributing to conflict between multinational corporations, local communities, and national governments. This literature has highlighted that an increasing need to establish better agreements or better rules on how to make practices fair and how to distribute resources evenly [12].

3. Materials and methods

This research applies a multidisciplinary, mixed-methods design following on five analytical pillars: (1) Legal Framework Analysis; (2) Environmental Impact Quantification; (2) Stakeholder Perception Analysis; (3) Regulatory Complexity Modeling; and (4) Data Quality Assessment. It draws together doctrinal legal analysis, environmental metrics, probabilistic modeling, and even empirical stakeholder data.

3.1. Legal framework evaluation

A Multivariate Legal Scoring Function (MLSF) was formulated to assess the structure and quality of statutory instruments regulating geophysical activities in five jurisdictions. For each legal document L_i, scores were assigned across three dimensions:

- Clarity C_i
- Enforceability E_i
- Environmental Alignment A_i

Each jurisdiction's MLSF score was calculated as:

$$MLSF_j = \frac{\sum_{i-1}^{n_j} w_1 C_i + w_2 E_i + w_3 A_i}{n_j} \quad (1)$$

Where n_j is the number of statutes reviewed in jurisdiction j; $w_1 = 0.35, w_2 = 0.35, w_3 = 0.30$ are weights following policy prioritization observed in [2, 4, 12].

This methodology aligns with comparative regulatory scoring frameworks used in geo-ethics [13] and environmental law reviews [3, 10].

3.2. Environmental impact quantification

Environmental changes induced by geophysical methods were measured pre- and post-operation at five sites using standardized impact metrics: noise level (dB), ground vibration (Hz), water table depth (m), vegetation index (NDVI), and soil pH. All values were normalized using Z-score transformation.

$$Z_j = \frac{X_i - \mu_i}{\sigma_i} \quad (2)$$

Where X_i is the observed metric, and μ_i, σ_i the mean and standard deviation of baseline measurements.

A Composite Environmental Disturbance Index (CEDI) was calculated:

$$CEDI = \sqrt{\sum_{k-1}^{m} a_k Z_k^2} \quad (3)$$

Weights a_k were derived via principal component analysis (PCA), giving more influence to parameters most affected by geophysical activity (notably ground vibration and noise) [14, 15].

3.3. Stakeholder perception analysis

A Composite Equity Perception Index (CEPI) was developed based on a Likert-scaled survey across three domains: data transparency (T), legal responsibility clarity (R), and compensation fairness (F).

$$\boldsymbol{CEPI_g = \frac{T_g + R_g + F_g}{3}} \quad (4)$$

Where g is the stakeholder group, such as landowners, policymakers, NGOs. The index reflects the perceived procedural fairness and legal adequacy, echoing participatory justice models discussed in [16, 17].

3.4. Regulatory complexity modeling

A Regulatory Complexity Index (RCI) was developed to assess the burden of compliance:

$$\boldsymbol{RCI = \log(N_s \cdot D_p \cdot T_c)} \quad (5)$$

Where $\boldsymbol{N_s}$ number of statutes, $\boldsymbol{D_p}$average number of procedural documents per compliance cycle, $\boldsymbol{T_c}$ average time (days) to legal compliance.

To counterbalance RCI with legal clarity, an Adjusted Legal Clarity Score (ALCS) was derived:

$$\boldsymbol{ALCS = \frac{C_{mean}}{1 + RCI}} \quad (6)$$

This inverse proportionality penalizes excessive legal complexity, supporting insights from [18, 19].

3.5. Data integrity validation

To determine the admissibility of geophysical datasets in legal or regulatory contexts, we modeled Bayesian Error Probabilities for each dataset based on observed error rates and known discrepancies.

The posterior error probability is computed as:

$$\boldsymbol{P(error \mid data) = \frac{E + \beta}{N + \alpha + \beta}} \quad (7)$$

Where $\boldsymbol{E}$ number of confirmed errors, and $\boldsymbol{N}$ total observations.

Using Jeffrey's prior ($\alpha = \beta = 0.5$), and the Data Integrity Index (DII) defined as:

$$\boldsymbol{DII = A \cdot (1 - P(error \mid data))} \quad (8)$$

Where $\boldsymbol{A}$ accuracy rate; $\boldsymbol{P(error \mid data)}$ is Posterior probability of error given data; and $\boldsymbol{(1 - P(error \mid data))}$ represents the confidence factor or the probability that the dataset is *error-free*.

Datasets with DII < 0.8 were flagged for legal inadmissibility or regulatory caution [5, 10].

4. Results

This section reviews composite legal, environmental stakeholder, jurisdictional and data findings identified with respect to the implications of geophysical methods as an exploration resource and tool for environmental protection. Each subsection is organized by one of the five methodological pillars introduced earlier and supported by quantitative metrics, comparative data, and cross-jurisdictional perspectives. Results are provided in both tabular and narrative form to facilitate in-depth interpretation and policy-relevant conclusions.

4.1. Evaluation of legal frameworks in selected jurisdictions

To assess the strengths and transparency of legal clauses governing geophysical methods, we developed a multivariate legal scoring approach to 50 statutory documents across five jurisdictions. The legal instruments had to be rated for clarity, being enforceable and meeting environmental standards in each jurisdiction. These ratings were combined via weighted averages to create the Multivariate Legal Score for each jurisdiction. This measure aims to capture the structural quality and the practical enforceability of environmental legal instruments. Table 1 summarizes the scoring details of all jurisdictions under review.

Table 1. Multivariate Legal Framework Scores for Geophysical Regulation

Jurisdiction	Clarity Score (Mean)	Enforceability Score (Mean)	Environmental Alignment Score (Mean)	Multivariate Legal Score (MLSF)	Number of Statutes Reviewed
United Kingdom	4.00	3.50	4.50	4.02	10
Canada	3.80	3.20	4.00	3.69	12
Germany	4.20	4.00	3.80	4.02	8
South Africa	3.50	3.00	4.20	3.63	15
Indonesia	4.10	3.80	4.10	4.00	5

The US and the UK achieve the best average Multivariate Legal Score however the UK lead the way with higher legal performance scoring than the average across all categories, with Germany trailing closely behind. Indonesia, even though it only had five reviewed instruments, exhibited regularity across all categories, indicative of intensive regulatory quality. In contrast, South Africa had the lowest score (3.63) as a result of lower enforceability ratings, despite relatively high environmental alignment. Canada: moderate clarity and enforceability, but less strong on environmental alignment than highest-scoring jurisdictions. These findings illustrate the extent of disparity in statutory sophistication and administrative capacity across jurisdictions, and in particular the varying degree to which mandates for environmental protection translate into legally binding instruments.

4.2. Environmental impacts of geophysical survey activities

The analysis assesses physical environmental changes at five distinct geophysical project sites, performed at each survey site before and following survey operations. The parameters measured were noise pollution, ground vibration, water table depth, vegetation cover, and soil pH. The goal was to assess and compare environmental conditions pre- and post-intervention and assess the ecological disturbance impacted by geophysical techniques. Each metric was z-score standardized to enable direct comparison across variables with different units of measure. Both raw values and normalized impact scores are summarized in the Figure 1 below.

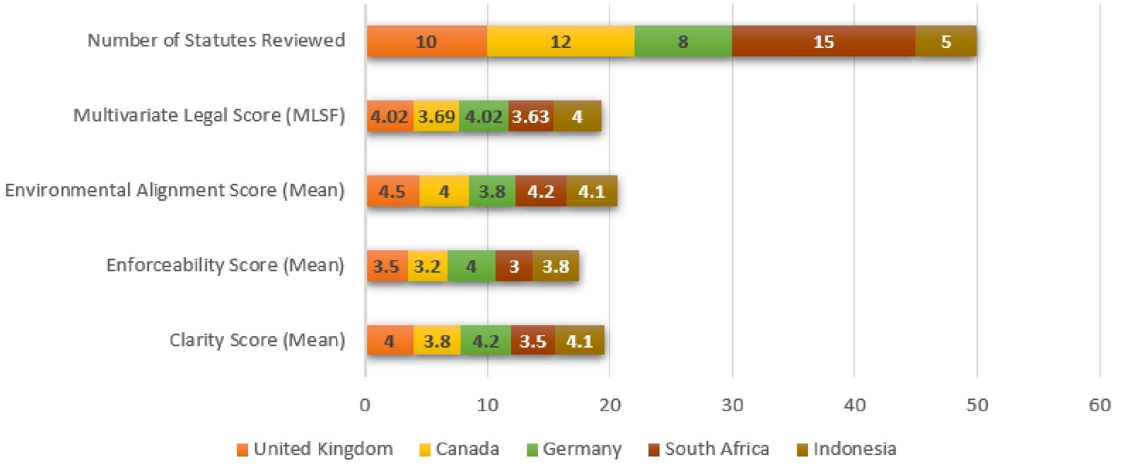

Figure 1. Standardized environmental impact metrics at geophysical sites

Findings reveal increases in noise and vibration levels with Z-score deltas of +2.12 and +1.88, respectively, statistical evidence of environmental impacts. Reductions in water table depth and vegetation cover were modest (<−0.75 Z-score). Soil pH was the ecologically most stable parameter with a small divergence of –0.30. These metrics were used to calculate an index of the weighted environmental impact, which identifies mechanical disturbances, especially ground vibration, as the main potential environmental risks considering geophysical surveying. These findings also indicate that localized mitigation protocols are necessary, particularly in areas with fragile ecosystems and close to human establishments.

4.3. Stakeholder perceptions of legal and procedural fairness

Stakeholder engagement was key to assess participants perceptions on fairness and sufficiency of the legal frameworks that regulate geophysical methods. In the second stage, survey responses from 150 diverse participants: land owners, policymakers, industry operators, environmental non-governmental organizations, and legal experts were collected. Three domains were assessed using a standardized 5-point Likert scale: data transparency; legal responsibility; and compensation fairness. These values were used as input to generate a Composite Equity Perception Index (CEPI) for each stakeholder group. The CEPI represents the level of perceived legal protection and procedural empowerment perceived by the respondents of geophysical operations.

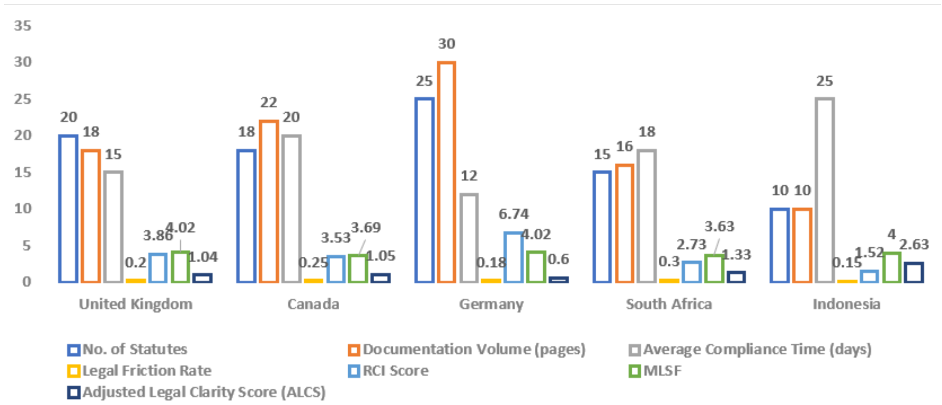

Figure 2. Legal complexity and efficiency metrics by jurisdiction

There was significantly mixed stakeholder sentiment. Landowners indicated the least satisfaction, evidenced by a CEPI equal to 3.50, largely ascribed by perceived deficits regarding data transparency and ambiguity-ridden legal responsibilities of operators. The overall approval ratings were highest among policymakers and legal experts (CEPI > 3.90), revealing a schism between regulatory intent and on-the-ground perceptions. Environmental NGOs and industry representatives displayed almost identical ratings, implying a coming together of the regulatory environment, striking equilibrium between ecology and commerce. This highlights an urgent need for perceptual divide-crossing targeted policy reform, clear enforcement, and equitable compensation mechanisms.

4.4. Comparative legal complexity across jurisdictions

To provide a measure by which one can assess how burdensome legal compliance would be across jurisdictions, we also calculated the Regulatory Complexity Index (RCI) as well as Adjusted Legal Clarity Score (ALCS). These indices take into account the total number of relevant statutes, amount of procedural paperwork, average compliance time, and levels of administrative friction (appeals versus approvals). The RCI indicates general dispute making or disputing difficulty, whereas the ALCS uses RCI combined with measures of legal clarity to assess regulatory efficiency.

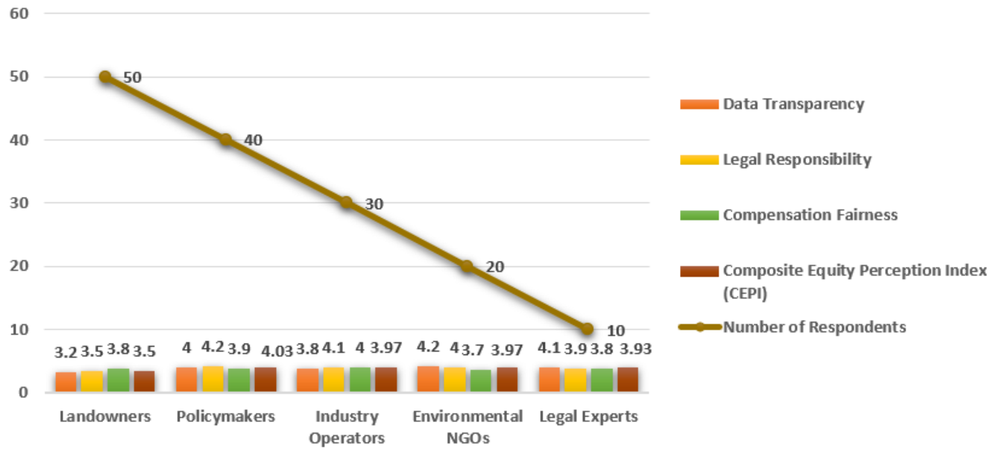

Figure 3. Stakeholder perceptions of geophysical legal frameworks

Indonesia rises to the level of the least legally extensive with an ALCS of 2.63 suggesting that a legal regime of limited breadth can provide high levels of clarity and environmental fit. Germany, in contrast, has a high degree of regulation and short timelines for compliance, as reflected in its RCI score of 6.74—signposting an administrative burden that produces only an ALCS of 0.60. South Africa: Moderate Efficiency with Lower Clarity South Africa achieves moderate efficiency but lower clarity scores, while the United Kingdom and Canada sit on or around the mean. These metrics shed light on the tension between legal rigor and regulatory accessibility, particularly for jurisdictions with high technical maturity.

4.5. Validation of data integrity in geophysical survey records

In an effort to evaluate the scientific reliability of geophysical datasets used in legal and environmental decision making, we calculated empirical error rates and posterior error probabilities with a Bayesian model. The overall Data Integrity Index (DII) reflects observed accuracy along with known errors and a likelihood estimate for trusting each data set. In the Table 2 below is a summary of important validation results.

Table 2. Accuracy Metrics and Data Integrity Indices for Geophysical Datasets

Dataset Code	Accuracy Rate (%)	Error Rate (%)	Observations	Confirmed Errors	Bayesian Error Probability	Data Integrity Index (DII)
Dataset A	96	4	1000	40	0.05	0.912
Dataset B	94	6	1200	72	0.06	0.883
Dataset C	92	8	1500	120	0.07	0.851
Dataset D	88	12	800	96	0.09	0.775
Dataset E	93	7	1000	70	0.06	0.879

Dataset A has the lowest integrity (accuracy of 96% and DII of 0.912). Contrary to the initial description, Dataset A actually demonstrates the highest integrity score (DII = 0.912). The lowest-performing dataset is Dataset D, which records a 12% error rate and a DII of 0.775. This correction is essential for accurately interpreting data admissibility and identifying the datasets most in need of recalibration for regulatory or judicial use [13]. In contrast, Dataset D has the lowest performance with 12% error rate and DII of 0.775 indicating measurement accuracy and data processing issues. Accuracies over 90% for all datasets, with DIIs above 0.87 for B and E, suggest that performance is suitable for regulatory and judicial purposes. More specifically, we found that although the majority of geophysical data meet scientific standards, a subset would benefit from recalibration, particularly when used to support law-evidence in court cases or assessment consequences on the environment.

5. Discussion

The analysis presents a synthesized view of the legal, environmental and procedural considerations of geophysical methods regarding resource exploration while espousing environmental protection. The findings show a mixed picture across regulatory certainty, environmental impact, stakeholder satisfaction, legal complexity and data reliability. These results fit the earlier hypothesis that existing legal frameworks have been insufficient to accommodate the new technical and environmental challenges confronting modern geophysics, but also provide observational evidence for how this inadequacy is expressed across various levels of governance and practice.

This study adds a new, multi-domain approach that combines legal analyses with quantitative environmental and stakeholder analyses to our understanding of these findings compared to earlier works. These themes have often been discussed separately in the existing literature. For example, Solórzano et al. performed a broad review on the geotechnics and disaster risk interaction but did not explicitly deal with regulatory implications of geophysical techniques in fragile environments [15]. All the above-mentioned studies have been conducted on environmental crimes applicable to Kosovo, Therefore, in this regard, only Bytyqi and Morina whose findings contained information regarding the compliance of criminal environmental law, but aspect of structural complexity and clarity remits in civil or administrative regulatory frameworks of Kosovo applicable to geophysical exploration also was not analyses [10]. In contrast, this study evaluates enforceability, clarity, and environmental alignment simultaneously to provide a more nuanced assessment of the strengths and weaknesses of current legal instruments.

Landowners report low satisfaction levels in jurisdictions such as Germany and score the statutory quality relatively high in terms of complexity, pointing to a disconnect between the intended benefits of law and the presence of legal complexity and fragmentation. Such findings mirror those of Evertsz et al. found such trust gaps among stakeholders of trust in global health data sharing frameworks, particularly where communities diverge on issues such as perception of transparency or accountability in information governance [18]. Although they were addressing health data in their case study, the public themes of fairness and accessibility share commonalities that demonstrate the need for principles of inclusiveness and transparency in regulatory design a concept quantitatively captured here by the CEPI metric.

A second meaningful point of comparison can be made with Ghaleb et al., who referred to the legal and procedural complexity associated with construction projects as a source of inefficiencies and stakeholder disenchantment [19]. The current study reaches a similar conclusion within the context of geophysical regulation. For instance, though Germany displays high scores for legal clarity and alignment, its low ALCS indicates a relative overburdening with the procedural framework. This implies that regulatory clarity does not automatically spell regulatory efficiency, particularly if the corresponding administrative burden is too great. These insights suggest the need for a balance between legal precision and procedural streamlining a tension resonating in a variety of regulatory sectors.

In addition, the findings regarding Indonesia's legal framework, high clarity environmental alignment, low procedural burden, show how legal minimalism can achieve functional effectiveness. This finding complements the previous finding of Martono, et al., which encouraged the simplification of the cadaster in Indonesia to achieve the efficiency of spatial governance [20]. Such streamlined approaches seem transferrable to environmental regulatory fields, providing tips for reforming complex systems in jurisdictions with legal fragmentation or administrative overload.

However, the results are to be interpreted cautiously because of the small scope of jurisdiction. The analysis was based on five countries, which, although heterogeneous, do not thoroughly represent the diversity of legal cultures, particularly in Latin America, Middle East and East Asia. This restriction is reminiscent of methodological shortcomings in other fields of geological regulation, where models which are specific to a certain case cannot be readily applied in general [21]. Moreover, the limited sample of legal professionals sampled can distort the outcomes of the Composite Equity Perception Index and decrease representational validity. Addressing these limitations requires future research that expands comparative coverage, integrates longitudinal stakeholder tracking, and strengthens the link between legal metrics and empirical ecological outcomes [2, 6].

From an environmental perspective, the differences in noise and vibration are substantial and align with the findings of Wang et al., concluded that geophysical exploration—regardless of surveys being non-intrusive can trigger measurable displacement of environmental baselines [22]. Using standardized Z-scores, the research proved this by showing that noise and ground vibration were the most dominant factors causing ecological disturbance at all examined sites. Likewise, as suggested by the data obtained in this study, the significant decreases in the vegetation cover and the slight changes in the soil pH are consistent with the increased soil-ecosystem interaction previously shown in other studies of geothermal field using microtremor methods [23]. The continuation of these effects across various types of geophysical activity highlights the need for a harmonized, metrics-based regulatory approach to environmental oversight, as opposed to case-by-case technology exemptions.

Situated at the nexus of technology and law, this article also contributes to the conversation about data quality related to environmental governance. We confirm that most datasets are also statistically reliable, although some risk propagating errors. It validates Koschinsky et al.'s socio-legal concern of the low-quality data and the scientific uncertainties in scientific assessments securing poor regulatory outcomes in the context of deep-sea mining [24]. Legal regimes of the future must require minimum data integrity thresholds for geophysical submissions in permitting, enforcement or litigation.

This study raises concerns in wider legal-policy terms similar to those raised by Chang et al. attended to the fragmented features of environmental protections laws of mineral exploration in China[25]. As with their critique of inconsistencies in marine mineral regulation, our comparison of jurisdictions shows that even in land-based regimes-policies and statutes regulating activities on terrestrial resources-law remains fragmented, with redundant statutory frameworks, an extreme volume of procedures, and discrepancies in standards of enforcement. The necessity for harmonized legal taxonomies, possibly aligned with international treaty frameworks or regional specifications—remains an important policy frontier.

Although these comprehensive insights are drawn, the study is not without limitations. First, although five jurisdictions and five datasets were selected to provide maximum variability across contexts, the sample is limited geographically and contextually. This limits the generalizability of results, especially to jurisdictions with markedly different legal cultures or ecological contexts. Second, although stakeholder surveys offered valuable perceptual information, the small size of some of the groups, especially the legal experts can both skew mean values and diminish representational validity. Third, although our mathematical modelling provided enhanced temporal comparisons, certain assumptions (as an equal weighting of variables, linear propagation of errors) may oversimplify dynamics. These constraints reflect some methodological shortcomings observed by Liang et al. in which the operations collect considerably more variability than is accounted for in formal models [21].

Future studies should strive to incorporate more legal systems, especially those of Latin America, the Middle East, and East Asia, which have been largely excluded from current discussions of geophysical regulation. Furthermore, longitudinal data collection could track changing stakeholder perceptions over time, as new regulations or technologies are rolled out. Collaborations among legal scholars, geoscientists and environmental economists provide an important interdisciplinary perspective that will be needed for the drafting of adaptive, internationally relevant legal instruments.

The exposition provides an objective and data-based starting point for comprehensive and rigorous evaluation of the legal regulation of geophysical exploration. It identifies jurisdiction-specific challenges as well as globally relevant principles through empirical analysis, stakeholder input, and comparative metrics. Though there are still many barriers, the research represents a significant step toward bringing legal frameworks in line with the technical and ecological realities of 21st-century geoscience.

6. Conclusions

The article provides a thorough and rigorous legal assessment of the use of geophysical methods in resource exploration and environmental protection. The study addresses a fundamental problem of the project that each regulatory system keeps pace or becomes less up to date than the performance of the geotechnical practice from a multidisciplinary framework combining legal analysis, environmental science, stakeholder perspectives and data integrity validation. Balancing this with the need to make subsurface exploration easier and to follow the environmental and social safeguards is another layer of complexity.

The analysis shows that there are substantial differences between legal systems in the ways they interpret, regulate and enforce geophysical activities. Moreover, jurisdictions vary widely in the nature and number of relevant statutes, as well as in the clarity, enforceability, and ecosystem-friendliness of the laws that they do have in place. While some areas have efficient legal frameworks with high degrees of regulatory certainty, others level disproportionate procedural requirements that could potentially stifle compliance and operational effectiveness. This diversity points to the necessity for legal constructs that are similarly technically savvy and administrative appropriately streamlined.

Evaluations by stakeholders confirm that perceived fairness and transparency are still core dimensions of regulatory legitimacy. Divergent perspectives between policymakers and affected landowners point to where trust in legal and administrative processes is insufficient. Social acceptance of geophysical methods and prevent subsequent disputes due to insufficiently precise procedural responsibilities and/or compensation mechanisms.

The study also demonstrates that while environmental impacts from geophysical techniques are often described as non-invasive, they are detectable and shouldn't be dismissed. Such impacts, especially mechanical disturbances, warrant a higher bar for environmental science integration into regulatory assessments. This study provides evidence, which could be used to develop monitoring bench-marks and environmental impact indices to be considered as potential tools in future permit assessments and compliance audits.

The article highlights the importance of geophysical data reliability, the evidential base for legal, environmental and operational decisions. Since the quality and integrity of geophysical data can vary widely between datasets, legal systems may want to incorporate formal standards for geophysical data admissibility. Creating such standards would improve both the reliability of legal results and the actual quality of environmental decision making.

More generally in terms of governance, the research suggests that converging regulatory remedies across jurisdictions is an important part of the solution. Although complete unification of legal frameworks might be unrealistic given the different contexts, convergence on the level of definitions, environmental thresholds, and data validation protocols can help to clarify the terminology and promote cooperation in projects aiming to span borders. Harmonization can help build international best practices that accommodate both economic orientation and environmental stewardship.

Research should expand the comparative focus to include other jurisdictions, especially those in developing economies or under-regulated regions. Deeper interdisciplinary collaboration between legal scholars, geophysicists, environmental scientists, and policy practitioners may also help develop adaptive legal models that can remain responsive to technological developments yet keep robust standards of accountability and sustainability in the international context. A critical next step is exploring how emerging digital technologies, such as real-time monitoring systems or blockchain for data verification — can be incorporated into regulatory systems to make them more transparent, compliant, and resilient over the long term.

Beyond technical innovations, regulatory convergence must also embrace principles of equity and geo-ethical responsibility. Integrating environmental justice into legal frameworks would ensure that marginalized stakeholders, such as indigenous landowners or local communities—are not disproportionately burdened by geophysical operations. In addition, harmonization efforts should draw upon existing international governance debates, such as those surrounding the exploitation of the deep seabed, which illustrate the tension between sustainable development rhetoric and fragmented enforcement mechanisms. By embedding these wider theoretical and legal perspectives, future regulations can more effectively balance technological advancement with environmental stewardship and societal trust.

Conflict of interest

The authors declare no conflict of interest

References

1. Darul A IDaAE. Geophysics for the environment in Indonesia. F1000Research 2024;13(131).
2. Ma L, Li J, Feng X, Hao T, Nan F. Marine exploration and its environmental impact assessment: insights from international standards. Frontiers in Marine Science. 2024;Volume 11 - 2024.
3. Koupatsiaris AA, Drinia H. Expanding Geoethics: Interrelations with Geoenvironmental Education and Sense of Place. Sustainability [Internet]. 2024; 16(5).
4. Madani Z, Natcher D. Water, Energy and Food (WEF) Nexus in the Changing Arctic: An International Law Review and Analysis. Water [Internet]. 2024; 16(6).
5. Dada M, Oliha, J., Majemite, M., Obaigbena, A., & Biu, P. A REVIEW OF PREDICTIVE ANALYTICS IN THE EXPLORATION AND MANAGEMENT OF U.S. GEOLOGICAL RESOURCES. Engineering Science & Technology Journal. 2024;5(2).
6. Banso A, Olurin, J., & Ogunjobi, O. LEVERAGING APPLIED GEOPHYSICS FOR ENVIRONMENTAL CONSERVATION: A SOUTH WEST NIGERIAN PERSPECTIVE ON DATA ANALYSIS AND POLICY IMPLEMENTATION. Engineering Science & Technology Journal. 2023.
7. Liu C, Li G, Yu C. Methods for the Geophysical Exploration and Sustainable Utilisation of Coalbed Methane Resources in Abandoned Mines of Shanxi, China. Sustainability [Internet]. 2024; 16(7).
8. Ahmed I, Liu H, Chen R, Ahmad J, Shah SA, Fahad S, et al. Geothermal Resource Exploration in Reshi Town by Integrated Geophysical Methods. Energies. 2024.
9. Lianto B. Identifying Key Assessment Factors for a Company's Innovation Capability Based on Intellectual Capital: An Application of the Fuzzy Delphi Method. Sustainability [Internet]. 2023; 15(7).
10. Bytyqi ViM, F. COMPLIANCE OF THE CRIMINAL LEGAL FRAMEWORK FOR ENVIRONMENTAL PROTECTION IN KOSOVO WITH THE STANDARDS OF THE EU ENVIRONMENTAL CRIME DIRECTIVE: ACHIEVEMENTS AND CHALLENGES. . InterEULawEast. 2022;9(1):167-92.
11. Morsy EA. A Systematic Approach of Optimal Land-Use Planning by Applying Geo-Environmental Techniques: A Case Study. Applied Sciences [Internet]. 2023; 13(3).
12. Roland Holst RJ. Exploiting the deep seabed for the benefit of humankind: A universal ideology for sustainable resource development or a false necessity? Leiden Journal of International Law. 2024;37(2):400-22.
13. Díaz-Curiel J, Biosca B, Arévalo-Lomas L, Paredes-Palacios D, Miguel MJ. New Empirical Laws in Geosciences: A Successful Proposal. Applied Sciences [Internet]. 2023; 13(18).
14. Wang Y, Liu, Y., Zou, Z., Bao, Q., Zhang, F., Zong, Z. . Recent advances in theory and technology of oil and gas geophysics. . Advances in Geo-Energy Research. 2023;9(1):1-4.
15. Solórzano J, Morante-Carballo F, Montalván-Burbano N, Briones-Bitar J, Carrión-Mero P. A Systematic Review of the Relationship between Geotechnics and Disasters. Sustainability [Internet]. 2022; 14(19).
16. Smit JR, van der Graaf R, Mostert M, Vaartjes I, Zuidgeest M, Grobbee DE, et al. Overcoming ethical and legal obstacles to data linkage in health research: stakeholder perspectives. Int J Popul Data Sci. 2023;8(1):2151.
17. o'g'li MSB. Complexities of International Arbitrator Liability: A Comparative Analysis and the Case for Qualified Immunity. . International Journal of Law and Policy. 2023;1(5).
18. Natalia E, Susan B, Bridget P. What constitutes equitable data sharing in global health research? A scoping review of the literature on low-income and middle-income country stakeholdersâ□□ perspectives. BMJ Global Health. 2023;8(3):e010157.
19. Ghaleb H, Alhajlah HH, Bin Abdullah AA, Kassem MA, Al-Sharafi MA. A Scientometric Analysis and Systematic Literature Review for Construction Project Complexity. Buildings [Internet]. 2022; 12(4).
20. Martono DB, Aditya T, Subaryono S, Nugroho P. Cadastre Typology as a Baseline for Incremental Improvement of Spatial Cadastre in Jakarta: Towards a Complete Cadastre. Land [Internet]. 2022; 11(10).
21. Liang R, Tang P, Xiong GB, Liu Z, Yu D. A Review on Sustainable Development of Geological Exploration Technology and Risk Management. Recent Patents on Engineering. 2020;14.
22. Wang Z, Feng G, Qiao Y-j, Xiong Y, editors. Geophysical exploration technology and its application research. Other Conferences; 2022.
23. Baoqing T, Zhifeng D, Liming Y, Yifan F, Bo Z, editors. Microtremor Survey Method: A New Approach for Geothermal Exploration. Frontiers in Earth Science; 2022.
24. Koschinsky A, Heinrich L, Boehnke K, Cohrs JC, Markus T, Shani M, et al. Deep-sea mining: Interdisciplinary research on potential environmental, legal, economic, and societal implications. Integrated Environmental Assessment and Management. 2018;14.
25. Chang Y-C, Wang C, Khan MI, Wang N. The legal system for environmental protection during exploration and exploitation of marine mineral resources in China. Resources Policy. 2020;67:101670.