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How Dutch subsurface professionals find, understand, and share information: a sector-wide survey

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Abstract. Safe and effective subsurface governance depends on information that is transparent, accessible, and independently verifiable. However, while much research has examined how geoscientists communicate with the public, little is known about how information moves among the professionals who research, regulate, conduct, and contest subsurface activities. We surveyed 135 professionals from more than 55 organizations across the Dutch subsurface sector, spanning research institutes, universities, national and regional government, advisory bodies, industry, and consultancy, on how they find, understand, trust, and share subsurface information, and where each breaks down. In general, finding or understanding information was not perceived as particularly difficult, but respondents still reported barriers to both: fragmentation across sources was by far the most frequently cited obstacle, and information was often insufficiently documented and explained. Intellectual property concerns and limited time and capacity mostly constrained sharing. Information flowed mainly within clusters of professionally similar organizations, with (environmental) NGOs and community organizations largely disconnected from the rest of the sector. Respondents strongly valued transparent communication of uncertainty but reported that it was insufficiently practiced and poorly taught within their organizations. Knowledge institutions scored highest on source credibility, including trustworthiness, while organizations at the sector's periphery were rated lower. The Dutch subsurface information system thus works reasonably well for those at its center but poorly reaches those at its edge. We identify four recommendations for policy and practice: a curated and standardized national information platform, the extension of information flows to civil society, guidance on communicating uncertainty, and greater transparency from less-credible sources.

1 Introduction

The subsurface is an important yet easily overlooked domain of modern society. It supports the infrastructure we depend on every day, such as cables, pipelines, and tunnels. It also contains resources like oil and gas that powered industrialization and that society still relies on today. Lastly, and increasingly important, the subsurface enables various technologies to advance a sustainable energy transition, including geothermal energy and the underground storage of hydrogen, carbon dioxide, and thermal energy (Gardiner et al., 2023). These applications continuously raise questions of safety, risk, and social equity,

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particularly when they occur against a backdrop of contested and sometimes disastrous past projects (Cuppen et al., 2020; Westlake et al., 2023).

The Netherlands has experienced this tension with the Groningen gas production. Decades of gas extraction in Groningen contributed to economic prosperity and energy security, while causing earthquakes, subsidence, and building damage, and a lasting crisis of trust in the institutions involved, ultimately leading to a parliamentary inquiry and the closure of the gas field in 2024 (Palomo-Vélez et al., 2023; Porada et al., 2024). The inquiry found that the information failures in Groningen resulted from structural shortcomings (Postmes et al., 2024). The operating company, NAM, held a de facto knowledge monopoly, rarely inviting independent scrutiny of its models and assumptions. Where it existed, knowledge about the adverse effects of gas extraction was concentrated in a small, closed network of operator, government-affiliated institutes, and one Dutch technical university (i.e., NAM, KNMI, TNO, SodM, TU Delft), and it was often not shared transparently (Tweede Kamer, 2023). This closed system kept out dissenting voices, making it very difficult for independent researchers to be taken seriously by the established parties. At the same time, the government lacked the in-house capacity to evaluate what it was being told. Large-scale public research programs (i.e., DeepNL and Knowledge Programme on the Effects of Mining) were launched only after roughly 50 years of extraction, and only after the damage from inadequate knowledge had already materialized.

These structures and the adverse impacts they caused took a toll on public trust in responsible institutions and science (Vojvodić et al., in press). Longitudinal research among Groningen residents shows that trust was undermined in two ways: residents doubted both the competence of the operating company and, more strongly, its integrity, that is, whether it genuinely cared about local impacts and was open about the risks involved (Liu et al., 2022). The Groningen case painfully shows that effective and safe subsurface governance requires independent, transparent information flowing freely among many actors: knowledge institutions, government, regulators, industry, and civil society (Busscher and Vojvodić, 2025).

However, three major conditions that contributed to many of the problems in the Groningen case remain and confront underground energy projects now being planned. The first condition is that the subsurface is inaccessible and abstract: no one can observe it directly, and even experts have to reason through models and proxies. Because the subsurface cannot be observed, laypeople tend to fill their knowledge gap with cultural and symbolic meanings that shape their perception of subsurface-related risks. Research shows that these associations are ambivalent and partly opposing: the underground as sacred vs. evil, holding knowledge vs. mysteries, posing threats vs. offering safety, and connecting to the past vs. the future (Lambert et al., 2025). Furthermore, human activity underground is, in some contexts, negatively perceived as “tampering with nature,” especially when it leads to induced seismicity (Cousse et al., 2025). In short, laypeople make sense of the subsurface in more intuitive, less rational, and less fact-based ways than experts (Gibson et al., 2016; Stewart and Lewis, 2017). However, even geoscientists themselves reason about the subsurface with both cognitive and affective components, and their mental models (i.e., internal representations) of the underground carry values and emotions as much as facts (Lacchia et al., 2020).

The second condition is that, due to the subsurface’s inaccessibility, uncertainty is inherent. Geoscientists introduce uncertainty through their (limited) measurements and models, and the entire subsurface sector must interpret uncertain findings and make decisions under uncertainty (Pérez-Díaz et al., 2020; Ralston and Kalmbach, 2018; de Waal and Schouten, 2020).

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Communicating that uncertainty is itself a problem, because uncertainty terminology in ground-related disciplines is not standardized and routinely misinterpreted across professional contexts (Erharter et al., 2024), and even apparently shared terms like "earthquake" or "tremor" can mean different things to expert audiences (Roberts et al., 2021). Beyond terminology, how uncertainty is presented can substantially influence perceptions: numeric disclosure, such as a range around a point estimate, tends not to undermine trust in the source, whereas vaguer verbal expressions often do (van der Bles et al., 2020). Moreover, the way probabilities are framed and anchored shapes how convincing they appear (Juanchich et al., 2025). How much uncertainty audiences want, and in what form, further depends on their expertise and prior trust in the source (Ratcliff et al., 2023).

The third condition is the fragmentation of subsurface information. Data on the subsurface and the authority over it are dispersed across many providers, platforms, and formats in the Netherlands – from the Dutch organization for applied scientific research (TNO) and the national weather forecasting service (KNMI) to ministries, regulators, municipalities, and operators. An actor seeking a complete picture of, say, induced seismicity risk near a planned site must assemble it from multiple, differently formatted, and not always interoperable sources.

These conditions are not unique to the Groningen gas production. They equally apply to the geothermal, energy storage, and CCS projects now entering planning and permitting across the Netherlands, where the same inaccessible subsurface, inherent uncertainty, and dispersed data must be navigated by an even broader and more diverse set of actors. While the inaccessibility of the subsurface and its uncertainties are difficult to resolve, the fragmentation of information can be addressed to enable a more effective, safe, and sustainable governance of the subsurface. The fragmentation of subsurface knowledge is even recognized as a problem at the highest policy level. In response to the parliamentary inquiry, the Dutch government established GeoKennisNL, a national program to improve the coordination, development, and sharing of knowledge about subsurface activities and their effects (Tweede Kamer, 2025). Its scoping phase, based on interviews and workshops with the organizations most closely involved in subsurface questions, identified the same core problems that motivate this study: subsurface information is fragmented and hard to find, difficult to understand for non-specialists, and provided by so many sources that apparent contradictions undermine trust (GeoKennisNL, 2025). Effective information exchange would require that professionals across the sector can find, understand, and trust the information they need, and that organizations produce and share it in ways that meet those needs.

However, we cannot improve that exchange without knowing more precisely how information moves among professionals today. To date, research has focused on how geoscientists can better communicate with the public to increase awareness and understanding of geoscientific subjects and risks. These studies generally suggest moving from one-way dissemination toward more dialogic and participatory models (Gibson et al., 2016; Illingworth, 2023; Stewart and Lewis, 2017). Far less is known about how professionals find, understand, and share information among themselves. A notable exception is Rodrigues et al.'s (2025) survey of the Portuguese geoscience community, which found that geoscientists' outreach predominantly targets students, teachers, and fellow researchers, rather than journalists, NGOs, and local communities. Evidence from Ireland further suggests that geoscientists rely on top-down, academic communication styles that do not appeal to diverse audiences (Marker,

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2008). The network of actors, channels, and practices through which subsurface information is produced, exchanged, and used is still barely mapped at the level of the whole sector. Even the national effort to address fragmentation has so far drawn primarily on the core network: GeoKennisNL's scoping phase concentrated on the thirty to thirty-five organizations most closely involved in subsurface issues, while consultancy and engineering firms, local and regional government bodies, and geothermal stakeholders were largely overlooked (GeoKennisNL, 2025).

We aim to close this gap by studying the full breadth of the Dutch subsurface sector, covering the major stakeholders involved in subsurface governance, use, and contestation, including academia and research, industry and consulting, government and regulation, and environmental and community organizations. The study traces what information professionals need, where they look for it, whether they find it, trust it, and understand it, and what information they share, with whom, and how. By capturing demand and supply side by side across all these groups, we can identify mismatches between them, where communication is most likely to break down. Given that the Groningen controversy was also a failure of trust, we examine how professionals assess the trustworthiness and other credibility aspects of the main organizations that provide subsurface information. We also attend closely to how professionals prefer uncertainty to be communicated, drawing on a body of work showing that uncertainty disclosure interacts in complex ways with format, framing, and audience characteristics (van der Bles et al., 2020; Gustafson and Rice, 2020; Knoblauch et al., 2018; Ratcliff et al., 2023). In doing so, we answer one overarching question and five sub-questions that focus on needs and accessibility (Questions 1 and 2), sharing (Question 3), and trust and uncertainty communication (Questions 4 and 5):

How does subsurface information flow among professionals in the Dutch sector, and where does it break down?

1. *What information do professionals need, and how do needs differ between stakeholder groups?*
2. *How accessible and comprehensible is the information they need?*
3. *How and with whom do professionals share information, and what constrains sharing?*
4. *How do professionals judge the credibility of the different organizations that provide subsurface information?*
5. *How do professionals prefer uncertain scientific information to be communicated?*

To inform efforts to improve information exchange across the Dutch subsurface sector, we conducted a large-scale study of Dutch professionals working in the subsurface. The next section explains how the survey was designed, distributed, and analyzed to achieve that.

2 Method

We employed a cross-sectional online survey design, consisting of a mix of open- and closed-ended questions. Data collection roughly spanned two months, between April and June 2026. The following sections describe the survey design and pre-testing, the recruitment process, and data analysis.

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2.1 Survey design and pre-testing

The survey comprised 38 questions across 8 thematic blocks: 6 open-ended and 32 closed-ended questions. After an introductory block covering eligibility and informed consent, the questions asked about respondents' demographic background, their information needs, the perceived accessibility and clarity of the information they use, their own and their organization's preferences for communicating uncertainty, how they share information with others, and their suggestions for improvement. Individual preferences for information about uncertain science were measured using a revised version of the PIUS-11 scale (Ratcliff et al., 2023). The scale was reduced from 11 to 7 items by excluding items with factor loadings below .70 in the original validation study, to limit length and respondent fatigue. The revised scale showed acceptable internal consistency after removing one additional item (Cronbach's α = .744). **Table 1** provides a full overview of the questions, their formats, and response scales.

The closed-ended questions were either single- or multiple-select, with multi-select questions allowing respondents to select all applicable options; many single- and multi-select questions also included an open "Other (please specify)" field so that respondents could add answers not on the list. Closed-ended numerical items used 5-point scales (e.g., Strongly disagree to Strongly agree; Extremely difficult to Extremely easy; Never to Very often). The survey was available in English and Dutch and hosted on the Qualtrics platform. The Dutch version was translated by the first author and reviewed by a native Dutch-speaking geoscientist. Each language version was then pre-tested with two native speakers. Feedback from the pre-tests led to minor phrasing adjustments. As the measured constructs remained unchanged, the pre-test data were included in the final analysis.

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Table 1

Overview of the Stakeholder Survey, by Block and Question Type

Survey block (no. of questions)	**Open-ended questions**	**Closed-ended questions**
1. Welcome 1 question	–	• Eligibility filter: Is your work related to the Dutch subsurface? – *single-select, dichotomous (yes/no); a "no" response ended the survey.*
2. Demographics 4 questions	Organization name.	• Organization type: *single-select, nominal (incl. an "Other" option).* • Primary job role: *single-select, nominal (incl. "Other" and "Prefer not to say").* • Years working on subsurface topics: *single-select, 5-category ordinal (0–2, 3–5, 6–10, 11–20, 20+).*
3. Information needs 4 questions	Topics for which adequate information cannot currently be found.	• Subsurface topics information is sought on: *multi-select, nominal (incl. an "Other" option).* • Purposes for seeking information: *multi-select, nominal (incl. an "Other" option).* • Search frequency: *single-select, 6-point ordinal ("Several times a week" to "Less than several times a year").*
4. Accessibility of information 5 questions	Suggestions for improving findability.	• Difficulty finding needed information: *single-select, 5-point Likert ("Very difficult" to "Very easy").* • Reasons information is difficult to find: *multi-select, nominal (incl. "Other").* • Organizations consulted, by frequency: *matrix, 5-point scale ("Never" to "Very often").* • Channels used, by frequency: *matrix, 5-point scale ("Never" to "Very often").*
5. Clarity of information 8 questions	Suggestions for improving understandability.	• Difficulty understanding used information: *single-select, 5-point Likert ("Very difficult" to "Very easy").* • Reasons information is difficult to understand: *multi-select, nominal (incl. "Other").*

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		• Extent information meets needs across five aspects (coverage, up-to-dateness, reliability, clarity, ease of access): *matrix, 5-point scale (“Not at all” to “Completely”).* • Providers’ clarity, transparency, competence, and trustworthiness, each rated per organization type (4 questions): *matrices, 5-point agreement scale (“Strongly disagree” to “Strongly agree”) plus a “Not applicable” option. Only organizations that were consulted at least sometimes were displayed (see the previous question block).*
6. Uncertainty in information 5 questions	–	• Most relevant uncertainty types to one’s work: *multi-select; selecting “none” skipped the rest of the block (aleatory, epistemic, none, other).* • Preferences for information about uncertain science (revised 7-question PIUS-11): *matrix, 5-point agreement scale (“Strongly disagree” to “Strongly agree”).* • How adequately uncertainties are explained in used information: *single-select, 5-point adequacy scale (“Far too little” to “Far too often”) plus a “Don’t know/Not applicable” option.* • Preferred ways of seeing uncertainty presented: *multi-select (incl. an “Other” option).* • Perceived effects of communicating uncertainty to the public (4 statements): *matrix, 5-point agreement scale (“Strongly disagree” to “Strongly agree”).*
7. Information production and sharing 7 questions	Suggestions for sharing information more effectively with professionals outside one's own organization/discipline.	• Personal involvement in producing information: *single-select (“yes, regularly”/”yes, occasionally”/”no”); a “no” response skipped the rest of this block.* • Types of information produced: *multi-select, nominal (incl. an “Other” option).* • Methods used to share information: *multi-select, nominal (incl. an “Other” option).* • Barriers to sharing information: *multi-select, nominal (incl. an “Other” option).*

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		• Groups information is shared with: *multi-select, nominal (incl. an "Other" option).* • Organizational norms on communicating uncertainty (4 statements): *matrix, 5-point agreement scale ("Strongly disagree" to "Strongly agree") plus a "Don't know/Not applicable" option.*
8. Suggestions for improvement 4 questions	Final comments.	• Organizations with which exchange should most improve: *multi-select, capped at three.* • Importance of seven information characteristics (reliability, transparency, independence, up-to-dateness, comparability, clear implications for policy and decision-making, understandability for non-experts): *matrix, 5-point scale ("Not at all" to "Extremely important").* • Additional formats or tools one would use: *multi-select (incl. an "Other" option).*

Note. Matrix questions present several sub-questions rated on a shared scale. In Block 5, the four provider-rating matrices displayed only the organizations a respondent reported consulting at least "sometimes" in Block 4. Uncertainty was defined in the survey as the degree of doubt or lack of complete certainty about geological processes, resources, and data, stemming from Earth's complexity and our limited access to the subsurface.

2.2 Recruitment

Drawing on a comprehensive stakeholder analysis of the Dutch subsurface sector, we identified more than 90 target organizations across academia and research, industry and consulting, government, and civil society (Schmidt, 2026). Organizations with which our CrossScale research team had existing professional contacts were contacted via email and asked to share the survey invitation with relevant colleagues and, where possible, through social media or newsletters. For the remaining organizations, we emailed a suitable contact person (e.g., the head of a program or department dealing with subsurface issues) and asked them to forward the invitation to the relevant people within their team and organization. Reminders were sent as needed.

To broaden reach, posters with a QR code linking to the survey were displayed at two professional conferences (the DeepNL Stakeholder Meeting in April 2026 and the Geothermal Forum NL in May 2026) and, for 10 days, on the public screens of the Department of Geoscience and Engineering at TU Delft. The first author also shared the invitation on LinkedIn, where fellow CrossScale project members with large networks in the Dutch geosciences reposted it. Given the snowball and forwarded

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recruitment strategy, a conventional response rate could not be calculated. As an incentive, participants could enter a lottery to win one of five €30 book vouchers.

2.3 Analysis

Respondents were included in the analysis if they completed at least 50% of the survey, to allow for meaningful data interpretation. Due to the survey's branching logic and optional questions, the number of respondents varies across items; the sample size is reported for each item (group). The quantitative data were analyzed in SPSS version 29. Responses to select-all-that-apply questions are reported as the percentage of respondents selecting each option, as these are not mutually exclusive. For single-select nominal items, responses are summarized by frequency and percentage; for single-select ordinal items, response distributions and means are reported. For inferential group comparisons, environmental protection agencies were grouped with regional and local governments, TNO Geological Survey respondents were grouped under advisory body, and sector associations were grouped with industry, based on comparable mandates and information profiles. Environmental and community organizations ($n = 2$) were retained in the descriptive analysis but excluded from group comparisons due to insufficient sample size. Stakeholder group differences in the selection of multi-select items (e.g., subsurface topics selected, purposes for seeking information) were examined using Fisher-Freeman-Halton exact tests, which are robust to sparse cell counts that arise with small groups. Stakeholder group differences on single ordinal items were examined using the Kruskal-Wallis test, with Bonferroni-adjusted pairwise comparisons to identify which groups differed when the omnibus test was significant. For batteries of related items rated on the same scale by all respondents (e.g., sources consulted, channels used), within-subjects differences across items were examined using repeated-measures ANOVA, with Greenhouse-Geisser correction applied where Mauchly's test indicated a violation of sphericity, and Bonferroni-adjusted pairwise comparisons used to locate significant differences between items. The first author analyzed the qualitative data from the open-ended questions through inductive and deductive coding in Atlas.ti. The resulting codes were discussed with the other authors to ensure consistency and agreement. The dataset underlying this publication is archived in the 4TU.ResearchData repository (Schmidt et al., 2026).

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3 Results

The results section is structured as follows: sample characteristics; information needs and accessibility; information sharing; uncertainty and its effects; improving the findability, understanding, and sharing of information; and preferred future tools and formats.

3.1 Sample characteristics

Of the 174 respondents who started the survey, 11 were excluded because their work was not related to the Dutch subsurface, and a further 28 were excluded for completing less than half of the survey. The final analytical sample comprised 135 respondents, with a median completion time of 23 minutes. Respondents worked for more than 55 organizations (***Table A 1*** provides an overview). National government bodies formed the largest group, including ministries responsible for economic affairs, climate policy, infrastructure, and water management, as well as the state-owned energy organization EBN. Universities and research institutes, advisory bodies, consultancy and engineering firms, and industry followed. Sector associations, environmental protection agencies, and regional and local governments were less well represented, and civil society was clearly underrepresented, with one respondent each from an environmental NGO and a community organization. Consistent with the dominance of research, national government bodies, advisory, and consultancy organizations in the sample, the most common job roles were researcher or scientist, policy officer or advisor, engineer or technical specialist, and consultant. Fewer respondents worked in management, specialized positions such as permitting, data and information management, investment, or spatial planning, and a handful in legal or communication roles. Respondents were notably experienced, with one-third having worked on subsurface issues for more than 20 years.
Table 2 provides an overview of the sample characteristics.

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Table 2

Sample Characteristics (n = 135)

Item	**Percentage (frequency)**
Organization type	
National government body	23.0 % (31)
University	16.3 % (22)
Advisory body	11.1 % (15)
Consultancy/engineering	11.1 % (15)
Research institute	10.4 % (14)
Industry/commercial operator	8.9 % (12)
Environmental protection agency	8.1 % (11)
Regional/local government	4.4 % (6)
Sector association	3.0 % (4)
Other	2.2 % (3)
(Environmental) NGO	0.7 % (1)
Community organization	0.7 % (1)
Job role	
Researcher/scientist	34.8 % (47)
Policy officer/advisor	24.4 % (33)
Engineer/technical specialist	14.8 % (20)
Consultant/advisor	10.4 % (14)
Other	8.1 % (11)
Manager/director	5.2 % (7)
Legal professional	1.5 % (2)
Communications officer	0.7 % (1)
Years of experience	
0-2	10.4 % (14)
3-5	15.6 % (21)
6-10	20.7 % (28)
11-20	20.7 % (28)
20+	32.6% (44)

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3.2 Information needs and accessibility

Respondents frequently searched for subsurface information: half searched several times per week, about one in five searched approximately once per week, and about an equal number searched several times per month. Only a small minority searched less regularly (***Table* 3**). No significant differences in search frequency across stakeholder groups were found (***Table B 1***).

3.2.1 What information is sought and why

Respondents sought information across a wide range of subsurface topics (***Table* 3**). Subsurface geology and geophysical interpretation were the most frequently cited (70.4%), followed by geothermal energy, induced seismicity or subsidence, and energy storage. Topics related to the shallow subsurface, groundwater, salt mining, and soil contamination were selected by about one-third, and cross-cutting or general subsurface topics by a similar share. Under “other,” respondents added further domains, including legislative and regulatory frameworks, critical raw materials, radioactive waste disposal, archaeology, and subsurface-surface interactions.

The purposes for seeking information were equally diverse (***Table* 3**). Risk assessment or preventive risk mitigation (51.1%) and scientific research (50.4%) were the most reported purposes, followed by project design/feasibility studies, public communication/stakeholder engagement, permit applications, and policy/regulation development, each cited by roughly one-third. Less common were operational management, decommissioning, regulatory supervision/enforcement, subsidy development, and damage claims/incident responses. Other purposes added by respondents included developing solutions to societal challenges related to the subsurface, deciding on objections and appeals to planned projects, and producing and disseminating data and knowledge.

Stakeholder differences emerged for 7 of 15 topics and 9 of 17 purposes (***Table B 1***). In both cases, they largely reflected what can be expected given the mandates and roles of the respective organizations. Research institutes were oriented towards geological and resource-related topics (e.g., oil, gas, energy storage, shallow subsurface) and towards scientific research as a purpose. Consultancy firms focused on subsurface geology and geological modeling to inform geotechnical investigations, project design, reservoir/field development, and investment decisions. Regional and local governments sought more information on soil and groundwater contamination and the shallow subsurface to support spatial planning, permitting, and policy development. Universities were consistently underrepresented across applied topics and purposes (e.g., resources, permitting, spatial planning) and only sought disproportionately more information about energy storage. National government bodies stood out for seeking information on oil/gas resources and for public communication/stakeholder engagement as a purpose. No significant differences were found for the remaining topics and purposes, suggesting broadly shared needs across the sector for subjects such as geothermal energy and induced seismicity, and purposes such as risk assessment and education.

The answers to the open question on what information respondents were lacking clustered into three themes (**Table 4**): specific geoscientific data domains (e.g., stress maps, fault-rock properties, geothermal reservoir data), regulatory and legal information (e.g., permit records, case law, allocation of regulatory authority), and integration and coverage gaps (e.g., cross-border data,

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surface-subsurface coupling). The largest group of missing topics, grouped under the first theme, was geomechanical and hazard-related: in-situ stress (maps, state, direction), fault-rock properties, well-test results tied to stress, natural and induced seismicity, subsidence, and the wetting/drying effects of changing water levels, and earthquake-damage records. Respondents repeatedly described data that existed but in the wrong form. Some respondents wanted it more granular (e.g., lithology with depth rather than formation name with depth; detailed measured geomechanical and geochemical values). Others wanted it to be more synthesized (e.g., interpreted geological data for decision-making rather than raw data; an overarching, coherent picture).

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Table 3

Descriptive Frequencies for Frequency Searching and Sharing, Topics Sought, Purposes, Barriers, Information Types Shared, Audiences, Exchange Priorities, Sharing Methods, Uncertainty Experienced, and Preferred Uncertainty Formats and Tools

Item	Percentage (frequency)
Search frequency (n = 134)	
Several times per week	50.0 (67)
Once per week	18.7 (25)
Several times per month	17.9 (24)
Once per month	6.0 (8)
Several times per year	6.0 (8)
Less than several times per year	1.5 (2)
Topics sought (n = 135)	
Subsurface geology and geophysical interpretation	70.4 (95)
Geothermal energy	59.3 (80)
Induced seismicity or subsidence	57.0 (77)
Energy storage	48.1 (65)
Oil and gas resources	46.7 (63)
Geological modeling	45.9 (62)
Oil or gas wells	40.7 (55)
Cross-cutting or general subsurface topics	36.3 (49)
Mining impacts (safety, health, etc.)	32.6 (44)
Underground infrastructure (cables, pipelines, etc.)	31.9 (43)
Groundwater supply/water aquifers	31.9 (43)
Shallow subsurface (incl. sand and gravel)	31.1 (42)
Salt mining	30.4 (41)
Underground thermal energy storage	29.6 (40)
Soil and groundwater contamination and remediation	23.7 (32)
Other	6.7 (9)
Purposes for seeking (n = 135)	
Risk assessment or preventive risk mitigation	51.1 (69)
Scientific research	50.4 (68)
Project design or feasibility studies	40.7 (55)
Public communication or stakeholder engagement	39.3 (53)
Preparing or evaluating permit applications	34.8 (47)
Developing policies or regulations	34.1 (46)
Spatial planning or area development	27.4 (37)

Item	Percentage (frequency)
Field or reservoir development	27.4 (37)
Informing investment or business decisions	27.4 (37)
Geotechnical investigation	26.7 (36)
Education or training	25.2 (34)
Operational management	11.9 (16)
Decommissioning	11.9 (16)
Regulatory supervision or enforcement	11.1 (15)
Damage claims or incident response	9.6 (13)
Developing subsidies	8.1 (11)
Other	3.7 (5)
Barriers to finding information (n = 133)	
Information scattered across many sources	78.2 (104)
Information not in a usable or interoperable format	28.6 (38)
Information is not publicly available (e.g., company-owned)	28.6 (38)
Too few local or site-specific details	28.6 (38)
Relevant information has barely been collected	19.5 (26)
Information is behind paywalls or otherwise restricted	18.0 (24)
Insufficient time to search	17.3 (23)
Difficulty judging which sources are reliable	14.3 (19)
Unclear where to look or which search terms to use	12.0 (16)
Other	8.3 (11)
Language barrier	4.5 (6)
Barriers to understanding information (n = 132)	
Underlying models/assumptions poorly explained	46.2 (61)
Too little explanation or context in general	28.8 (38)
Too much jargon	21.1 (28)
Technically too complex	19.7 (26)
Too much detail	17.4 (23)
Contradictions between sources	16.7 (22)
Visualizations (maps/graphs) hard to interpret	15.2 (20)
Difficulty translating information into one's own work	10.6 (14)
Other	6.1 (8)
Foreign language	5.3 (7)

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Item	Percentage (frequency)
Frequency sharing information (n=126)	
Regularly	46.0 (58)
Occasionally	27.8 (35)
Never	26.2 (33)
Information types shared (n=92)	
Technical/geological data or models	66.3 (61)
Scientific research outputs	53.3 (49)
Public communication or outreach materials	34.8 (32)
Project designs or feasibility studies	33.7 (31)
Permit and license applications	28.3 (26)
Advice on policy or permitting	28.3 (26)
Educational or training materials	28.3 (26)
Data on field or reservoir development	22.8 (21)
Risk or safety assessments	22.8 (21)
Policy or strategy documents	18.5 (17)
Operational monitoring reports	18.5 (17)
Gas/oil well design	8.7 (8)
Laws, regulations, guidelines	7.6 (7)
Regulatory or compliance reports	7.6 (7)
Environmental/social impact assessments	5.4 (5)
Damage assessment or compensation documents	4.3 (4)
Audiences for shared information (n=92)	
Internal colleagues/management	83.7 (77)
Industry and commercial stakeholders	55.4 (51)
National government bodies	54.3 (50)
Specific scientific/academic organizations	51.1 (47)
Advisory bodies	39.1 (36)
(Inter)national research community	39.1 (36)
Regulators and enforcement bodies	32.8 (30)
Provinces	31.5 (29)
Municipalities	31.5 (29)
Sector and trade associations	23.9 (22)
General public	22.8 (21)
Community organizations and local residents	16.3 (15)
(Environmental) NGOs	3.3 (3)

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Item	Percentage (frequency)
Prioritized organizations for increased exchange (n=125)	
Dutch research institutes	26.4 (33)
National government bodies	24.0 (30)
Advisory bodies	22.4 (28)
Regulators and enforcement bodies	20.8 (26)
General public	20.8 (26)
Provinces	20.0 (25)
Municipalities	17.6 (22)
Industry and commercial stakeholders	17.6 (22)
Dutch universities and academic groups	16.0 (20)
Community groups and local residents	11.2 (14)
Water boards	10.4 (13)
Sector and trade associations	9.6 (12)
International research community	9.6 (12)
(Environmental) NGOs	2.4 (3)
Sharing methods (n=92)	
Conferences, workshops, professional meetings	70.7 (65)
Formal reports or publications	65.2 (60)
Direct sharing with specific stakeholders	55.4 (51)
Digital platforms and repositories	53.3 (49)
Upload to internal project/data drive	50.0 (46)
Organizational websites or press releases	40.2 (37)
Social media or newsletters	28.3 (26)
Confidential submission to a regulator/government body	27.2 (25)
Public submission to a regulator/government body	17.4 (16)
Barriers to sharing (n=92)	
Intellectual property or commercial sensitivity	46.7 (43)
Lack of time or capacity	39.1 (36)
Legal or regulatory restrictions	34.8 (32)
Difficulty translating information for non-specialists	34.8 (32)
Lack of a clear mandate or responsibility	20.7 (19)
Information not in an easily shareable format	22.8 (21)
Lack of suitable sharing platforms/systems	18.5 (17)
Slow internal approval processes	17.4 (16)
Data quality insufficient for sharing	17.4 (16)
Uncertainty about the relevant audience	16.3 (15)

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Item	**Percentage (frequency)**
Lack of feedback on the usefulness of shared information	10.9 (10)
Organizational culture discourages external sharing	6.5 (6)
Uncertainty experienced (n=125)	
Epistemic	85.6 (107)
Aleatory	58.4 (73)
None	4.0 (5)
Preferred uncertainty format (n=125)	
Best estimate plus numeric range	73.6 (92)
Visual representation (maps, graphs, etc.)	64.8 (81)
Multiple scenarios with descriptions	50.4 (63)
Percentile formats (e.g., P10–P50–P90)	44.0 (55)
Best estimate with a qualitative uncertainty term	12.0 (15)
No explicit uncertainty information	8.0 (10)
Other	4.0 (5)
Preferred tools and formats (n=122)	
Integrated national knowledge database	87.7 (107)
Overview map of research and networks	68.9 (84)
Regular knowledge days and sector events	46.7 (57)
Regular sector newsletter	32.0 (39)
Interactive future scenario tool (e.g., for subsidence)	32.0 (39)
Short video explainers or animations	32.0 (39)
Online training modules or webinars	26.7 (36)
Cheat sheets explaining key concepts	25.4 (31)
Ask-an-expert service for the public	24.6 (30)
Standardized Q&A/FAQ materials	19.7 (24)

Note. Values are the percentage of respondents who selected each option. Search frequency and sharing frequency were single-select items. The other items were multi-select, so column totals exceed 100%

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Table 4
Topics on Which Information is Currently Missing

Theme	Subcode
Specific geoscientific data domains	• Rock, stress, and reservoir properties: stress maps, state, and direction; measured geomechanical and geochemical values; core intervals and photos; log-based porosity and permeability; fault-rock properties; well-test results tied to stress; lithology-with-depth rather than formation-name-with-depth; geothermal reservoir thermal/mechanical properties; deep-drilling additive chemistry. • Groundwater and shallow subsurface: recent groundwater levels, salinity, flow, aquifers, protection zones, and detailed cover-layer data. • Geothermal energy: general potential and reservoir data, with a pointed note that ThermoGIS figures are partly outdated relative to SCAN and recent work, yet still feed national policy. • Seismicity and hazard impacts: natural-seismicity monitoring gaps in the Roerdalslenk (only heavier events detectable), reported earthquake-damage records, and wetting/drying effects of water-level change. • Interpreted geological data and models: interpreted (not raw) geological data used for decision-making at SodM, geophysical models of the Netherlands, and geological outcrops. • Locations of existing installations: underground water-storage installations. • Emerging uses and resources: critical-raw-materials potential.
Regulatory and legal information	• Rulings: past judicial decisions (the 1900–1975 case law). • Permit and decision records: the documentary trail of specific authorizations: current permits (poorly disclosed and fragmented across NLOG/mining permits) and older production plans and decisions. • Allocation of regulatory authority: who is the competent authority for what, and the coherence of responsibilities (raised through the Water Framework Directive).
Integration and coverage gaps	• Cross-border data: "geology does not stop at the border," but databases do; integration is left to the user. • Surface–subsurface coupling: the gap is the link to above-ground information (e.g., risk maps for surface installations), not the subsurface data itself. • Site-integrated representation: the wish to draw a line anywhere and get a cross-section with every interpreted layer projected onto it. • Strategic, long-term overview: an overarching vision of how it all coheres, framing for 10–20 years and orienting for 100.

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3.2.2 What sources and channels are used

Respondents were asked how frequently they consulted different types of organizations and information channels. Both showed significant within-sample variation ***Table B*** 3). Among organization types, research institutes and advisory bodies were consulted most frequently (sometimes – often), followed by universities, which were consulted significantly more often than the remaining sources, except national government bodies (***Table* 5**). National government bodies occupied an intermediate position and were consulted significantly more often than provinces and municipalities. NGOs and community organizations were consulted least frequently (never – rarely), significantly below all other source types. The other sources, including industry, regulators/enforcement bodies, provinces, municipalities, and sector associations, fell within the middle range (rarely – sometimes), with no significant differences among them (***Table B*** 3).

Among channels, public digital platforms and repositories, such as NLOG and DINOloket, were used most frequently (often; ***Table* 5**), significantly above every other channel (***Table B*** 3). Peer-reviewed literature, gray literature, internal documents, and conferences/professional events formed a second tier (sometimes – often), within which the only significant difference was that gray literature was used more than conferences. Organizational websites were used significantly less often than peer-reviewed literature, gray literature, and internal documents, but did not differ significantly from conferences. Social media/newsletters and AI language models/domain-specific AI tools were used least frequently (rarely), both significantly below all other channels.

Stakeholder differences in both source consultation and channel use revealed a consistent in-group pattern (***Table B*** 2). Respondents consulted the source corresponding to their own organization type more frequently than other groups did. This was clearest for regional and local governments, which consulted provincial and municipal sources far more often than any other group. The one apparent exception – advisory bodies consulting research institutes more than research institutes themselves did – likely reflected the TNO-heavy composition of the advisory-body group. These respondents probably draw on TNO's broader research outputs classified under the research institutes category.

Channel use showed fewer group differences, and the patterns that did emerge were consistent with what was expected from the respective groups' work procedures. Universities used peer-reviewed literature significantly more than industry and national government bodies, while regional and local governments used it significantly less than nearly all other groups. Advisory bodies consulted gray literature significantly more than industry, and national government and advisory bodies used internal documents significantly more than universities. AI tools produced a significant omnibus test, but no pairwise comparison survived Bonferroni correction. The four remaining channels (i.e., public digital platforms, organizational websites, social media and newsletters, and conferences and meet-ups) did not differ significantly across groups.

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3.2.3 What makes finding and understanding information difficult

On average, respondents reported that both finding and understanding subsurface information were neither difficult nor easy (***Table* 5**), with no stakeholder differences for either (***Table B*** 2).

The barriers respondents cited, however, were more revealing. The most common barrier to finding information was fragmentation: 78.2% reported that information was scattered across many sources (***Table* 3**). The next most common barriers, at around one in three, were information not in a usable or interoperable format, information not publicly available (e.g., company-owned), and too few local or site-specific details. Further barriers included paywalled or restricted information, insufficient search time, difficulty judging source reliability, and unclear search strategies (i.e., where and how to look). Under "other," respondents identified additional obstacles, including poor metadata, technical language and jargon, information buried in unindexed documents, poor search tools, lacking platform usability, the absence of older records, and non-digitized materials held outside the respondent's own organization.

Understanding was most often hampered by poorly explained underlying models or assumptions, cited by 46.2% (***Table* 3**). Around one in three reported too little explanation or context in general, and roughly one in five reported too much jargon or technical complexity. Less frequently cited were too much detail, contradictions between sources, difficulty interpreting visualizations such as maps or graphs, difficulty translating information into one's own work, and a foreign-language barrier. Under "other," respondents flagged insufficient metadata, unclear data origin, poor website navigability, limited legibility of older records, a lack of state-of-the-art syntheses, and a lack of standardization, harmonization, and interoperability across sources.

Stakeholder differences were minimal for both sets of barriers (***Table B 1***). For finding information, only insufficient search time (more common among national government bodies) and a foreign-language barrier (more common at universities and research institutes) showed significant differences. For understanding, only contradictions between sources and a foreign-language barrier (both more common among research institutes) differed across stakeholders.

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Table 5

320 *Mean Values of Difficulty, Source Consultation, Channel Use, Information Quality, Importance of Information Characteristics, Organizational Uncertainty Norms, Preference for Uncertainty, Uncertainty Effects, and Adequate Uncertainty Explanation*

Item	*M*	*SD*	Verbal label
Difficulty finding information (n=133)	3.11	0.91	Neither nor
Difficulty understanding information (n=132)	3.48	1.030	Neither nor
Sources (organization types consulted; n = 129-132)			
Research institutes (e.g., TNO, KNMI, PBL)	3.84	.972	Sometimes – often
Advisory bodies (e.g., Mijnraad, TNO-GDN)	3.55	1.185	Sometimes – often
Universities and academic groups	3.35	1.120	Sometimes
National government (e.g., RVO, EZK, EBN)	2.98	1.193	Rarely – sometimes
Industry (incl. operators)	2.62	1.109	Rarely – sometimes
Regulators/enforcement bodies (e.g., SodM)	2.52	1.030	Rarely – sometimes
Sector and trade associations	2.40	1.115	Rarely
Provinces	2.32	1.189	Rarely
Municipalities	2.19	1.180	Rarely
(Environmental) NGOs	1.76	.814	Never – rarely
Community organizations	1.63	.852	Never – rarely
Channels (n = 131-132)			
Public digital platforms/repositories (e.g., NLOG)	4.21	.989	Often
Peer-reviewed literature (e.g., academic journals)	3.61	1.202	Sometimes – often
Gray literature/technical reports (e.g., TNO, EZK)	3.64	.966	Sometimes – often
Internal documents or information	3.62	1.126	Sometimes – often
Conferences, workshops, professional meet-ups	3.32	.832	Sometimes
Organizational websites or press releases	3.04	.823	Sometimes
Social media or newsletters	2.39	1.123	Rarely
AI LLMs or domain-specific AI tools	2.34	1.118	Rarely
Information quality (n=132)			
Coverage	3.42	.762	Moderately
Up-to-dateness	3.30	.759	Moderately
Reliability	3.58	.731	Moderately – to a large extent
Clarity	3.45	.734	Moderately
Ease of access	3.27	.820	Moderately
Importance information characteristics (n=122)			
Up-to-dateness	3.62	.775	Moderately – very important
Reliability	4.30	.691	Very important
Transparency about uncertainty and limitations	4.05	.759	Very important

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Item	*M*	*SD*	Verbal label
Independence of provider (no conflict of interest)	3.84	.823	Moderately – very important
Comparability and consistency	3.75	.865	Moderately – very important
Clear explanation of policy/decision implications	3.48	1.077	Moderately important
Understandability for non-specialists/public	3.16	1.185	Moderately important
Organizational uncertainty norms (n=88-91)			
Expectation to communicate transparently	4.45	.671	Agree
Expectation to avoid confusion	2.50	1.174	Disagree – neither nor
Expectation to avoid controversy	2.17	1.047	Disagree
Adequate guidance for communication	3.62	.931	Moderately – to a large extent
Preference for learning about uncertainty (n=124)	4.14	.442	Agree
Perceived uncertainty effects (n=125)			
Realistic public expectation	3.75	.858	Neither nor – agree
Improved informed judgments	3.61	.924	Neither nor – agree
Decreased public trust	2.50	1.037	Disagree – neither nor
Decreased public support	2.87	1.032	Disagree – neither nor
Adequate explanation of uncertainties (n=114)	2.23	.674	Somewhat too rare

Note. Items were rated on 5-point scales, with verbal labels corresponding to the nearest scale anchor for each mean.
Difficulty: 1 = extremely difficult, 2 = somewhat difficult, 3 = neither difficult nor easy, 4 = somewhat easy, 5 = very easy.
Frequency: 1 = never, 2 = rarely, 3 = sometimes, 4 = often, 5 = very often.
Information quality: 1 = not at all, 2 = slightly, 3 = moderately, 4 = to a large extent, 5 = completely.
Information needs: 1 = not at all important, 2 = slightly important, 3 = moderately important, 4 = very important, 5 = extremely important.
Uncertainty norms, preference and effects: 1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, 5 = strongly agree.
Adequate explanation of uncertainties: 1 = far too little, 2 = somewhat too little, 3 = about the right amount, 4 = somewhat too often, 5 = far too often.

3.2.4 Experienced information quality, source credibility, and important information characteristics

Respondents rated the quality of existing information moderately positively across all five dimensions (***Table* 5**): reliability was rated significantly higher than up-to-dateness and ease of access; no other pairwise differences were significant (***Table B*** 3). No significant differences in stakeholder group emerged for any of the five dimensions (***Table B*** 2).

Beyond the quality of the information itself, respondents also rated the organizations whose information they used on four dimensions: clarity, transparency about methods and limitations, perceived competence, and overall trustworthiness. Significant differences emerged across information sources (***Table B*** 4). Research institutes received the highest mean rating of any source on all four constructs, closely followed by universities and advisory bodies, which rated similarly highly on competence and trustworthiness in particular. The lowest-rated sources differed somewhat by construct: industry and commercial operators, provinces, and municipalities received the lowest clarity and transparency ratings, while community organizations, (environmental) NGOs, and municipalities received the lowest competence and trust ratings. Trust in regulators/enforcement bodies showed wider variability than trust in any other source, suggesting that respondents' experiences with regulatory information differed.

The importance of seven information characteristics showed some differing weight across items (***Table* 5**): reliability and transparency about uncertainty and limitations were rated as very important and significantly higher than all other items, with reliability also significantly exceeding transparency, but transparency not exceeding independence of provider (***Table B*** 3). Independence of provider, comparability/consistency, and up-to-dateness formed a moderately-to-very-important middle cluster, not significantly distinguished from each other; and clear explanation of policy and decision implications and understandability for non-specialists/public were rated lowest, as moderately important, with understandability significantly below every other item. Significant stakeholder differences only emerged for one of the seven aspects. For non-specialists/public understandability, regional and local governments showed significantly higher mean ranks than industry, consultancy, and university at the uncorrected level, suggesting these government respondents considered understandability more important than industry, consultancy, and academic respondents. However, none of these differences remained significant after Bonferroni correction for multiple comparisons (***Table B*** 2).

3.3 Information sharing

Most respondents reported producing information or data (46% regularly and 27.8% occasionally; ***Table* 3**). The 26.2% who did not produce any were not asked the following questions.

3.3.1 What is shared, how, and with whom

The most produced information types were technical and geological data or models, reported by two-thirds of respondents (66.3%), and scientific research outputs, reported by just over half (53.3%). Public communication, educational materials, permit and license applications, and policy or permitting advice were produced by around one-third. In contrast, regulatory and compliance-related materials (laws and regulations, compliance reports, environmental/social impact assessments, damage assessments) were produced comparatively rarely. The dominant methods of sharing these information types were conferences, workshops, and professional meet-ups (70.7%), followed by formal reports/publications (65.2%). Direct stakeholder sharing, digital platforms, and internal project drives were all used by roughly half the sample, with social media and regulatory submissions trailing well behind. Information was shared most often with internal colleagues or management (83.7%), followed by industry, national government bodies, and academic organizations, each at roughly half of the sample. Community organizations and (environmental) NGOs were named comparatively rarely. Full frequencies are reported in ***Table* 3**.

Stakeholder differences emerged across information types, methods, and audiences, and largely followed the in-group pattern observed for source consultation (***Table B 1***). Universities directed their sharing toward academia (scientific research outputs,

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educational/training materials, formal publications, the research community) and away from governmental audiences (policy documents, permits, policy advice, national government bodies, regulators/enforcement bodies, advisory bodies, provinces, and municipalities). They produced more technical and geological data or models. Regional and local governments showed a mirror image: more policy information (i.e., policy documents and advice) shared with governmental audiences (i.e., national government bodies, provinces, and municipalities), and less with academic and technical audiences. Research institutes, together with advisory bodies, were more likely to produce scientific research outputs, share with national government bodies, regulators/enforcement bodies, and advisory bodies, and use digital platforms and repositories. Industry was more likely to produce permit applications and well design information, to use regulatory submissions more extensively, and to share less through conferences/workshops or organizational websites. Advisory bodies stood out for their breadth, being overrepresented in the use of formal reports, organizational websites/press releases, and conferences/workshops. National government was more likely to share with other national government bodies and less likely to share with the (inter)national research community.

3.3.2 What prevents sharing

Intellectual property or commercial sensitivity was the most frequently cited barrier (46.7%), followed by time and capacity constraints (39.1%). Regulatory or legal constraints and difficulty translating information for non-specialists were cited by around one in three, while structural and quality-related barriers, such as unclear mandates for sharing, slow internal approval processes, a lack of sharing platforms, or insufficient data quality, were cited by around one in five (***Table* 3**). Organizational culture discouraging external sharing was cited comparatively rarely. Almost none of the 12 barriers showed differences across stakeholder groups. The only exception was information not being in an easily shareable format, cited more often by regional and local governments and less so by national government bodies (***Table B 1***).

3.3.3 Where the exchange should improve

When asked to prioritize up to three organizations for increased information exchange, Dutch research institutes and national government bodies were most often named, each by about a quarter of respondents (***Table* 3**). Advisory bodies, regulators/enforcement bodies, provinces, and the general public were listed by about one in five, while water boards, sector associations, the international research community, and (environmental) NGOs were named comparatively rarely. Two stakeholder differences emerged (***Table B 1***): Advisory bodies were more likely to prioritize the international research community, consistent with the TNO-heavy composition of that group, while universities were more likely to prioritize increased exchange with the general public.

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3.4 Uncertainty and its effects

3.4.1 Encountering and communicating uncertainty

The vast majority of respondents reported encountering epistemic uncertainty in their work (85.6%), defined as uncertainty arising from a lack of knowledge or insufficient data (***Table*** **3**). Aleatory uncertainty, which results from irreducible natural geological variability, was encountered by just over half (58.4%). Only five respondents indicated that uncertainty did not play a role in their work. No stakeholder differences emerged for either type of uncertainty (***Table B 1***). Respondents who selected "other" described forms of uncertainty that went beyond the data itself and referred to the decision, the institutions, and the communication around it: normative or decisional uncertainty (e.g., when a risk is acceptable, or which criteria apply in policymaking and monitoring), uncertainty as a trust and independence problem tied to the interests of information producers, and uncertainty as a communication challenge at the science-society boundary (e.g., challenge of explaining and justifying uncertain results to political and public audiences).

When asked which formats for communicating uncertainty they found most useful, respondents most strongly endorsed a best estimate plus a numeric range (73.6%), followed by maps or graphs that visually show uncertainty (64.8%). Multiple scenarios with descriptions and percentile formats (e.g., P10–P50–P90) were each endorsed by around half of respondents. In contrast, a best estimate with a qualitative uncertainty term or, with no explicit uncertainty information, was endorsed by the fewest respondents (***Table*** **3**). Two stakeholder differences emerged: percentile formats were more often endorsed by advisory and national government bodies, and multiple scenarios were more often endorsed by research institutes and less often by industry and consultancy (***Table B 1***). Respondents who selected "other" cautioned that the focus should be less on display format and more on transparency about the basis and causes of uncertainty, fitness for purpose, and comparisons with other risks for context; one respondent noted that visual formats can mislead non-experts, likely because they could be hard to interpret without the right expertise.

On average, respondents agreed that their organization expected them to communicate uncertainties transparently and disagreed that it expected them to simplify or omit uncertainties to avoid confusion or controversy (***Table*** **5**). Notably, the spread was larger for the latter two items, suggesting that organizations differed markedly in how much they expected employees to refrain from communicating uncertainty to avoid adverse effects. Respondents agreed somewhat less that their organization provided adequate guidance on communicating uncertainty effectively (***Table*** **5**). No stakeholder differences were found for any of the organizational norms (***Table B*** 2). Respondents also expressed a strong individual preference for learning about uncertain science and for having limitations and uncertainties communicated transparently (***Table*** **5**), with no differences across stakeholders (***Table B*** 2).

3.4.2 Beliefs about uncertainty and its effects

Respondents held broadly positive views about the effects of communicating uncertainty transparently to the public: they tended to agree that it leads to more realistic expectations about the implications of subsurface projects or decisions and helps

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the public make better-informed judgments about subsurface issues (***Table* 5**). In contrast, respondents tended to disagree that transparently communicating uncertainty decreases public trust in experts or makes it harder to obtain public support for projects or decisions. Again, the spread for the latter two items was wider, indicating more divergent views among respondents. Only one stakeholder difference emerged: advisory bodies were more likely than research institutes to agree that transparent communication leads to more realistic expectations (***Table B*** 2).

These positive beliefs coexisted with a perceived implementation gap. Respondents rated the extent to which uncertainties were explained in the information they used for their own work as somewhat too rare (***Table* 5**), with no stakeholder differences (***Table B*** 2).

3.5 Improving the findability, understanding, and sharing of information

The survey included three open-ended questions asking how the findability, understanding, and sharing of subsurface information could be improved. Because the answers overlapped substantially across the three questions, we report them together under five themes rather than question by question, noting where a theme spanned more than one question.

3.5.1 Accessibility and discoverability

The most common suggestion was to bring subsurface information together in one place. Respondents described two versions of this. Some wanted a single repository holding all available data: "all information in one spot," or "one integrated platform: DINOloket, ThermoGIS, NLOG." Others preferred a central catalog that links to sources still maintained by their original owners: "a central site containing references to datasets … still maintained by the parties themselves." One respondent added that gathering data in one place was not enough in itself; the content should be selected and organized such that the purpose dictates it.

Beyond a central access point, respondents asked for better tools to find and extract existing information. Suggestions included more flexible, AI-supported search, indexing, and OCR (optical character recognition), making old, scanned reports searchable; enabling querying of a database and exporting results (for example, all offshore wells with a particular log type); and allowing searches by location or coordinates. Several respondents also wanted to view information spatially (i.e., on maps, in three dimensions, or as cross-sections that combine several layers for a given location) so that the subsurface becomes legible at a glance, including to non-specialists. Finally, respondents singled out local and shallow subsurface information as especially hard to access, describing it as fragmented or a "black box": unclear which organization held it, in what format it existed, or whether it existed at all.

3.5.2 Understanding and interpretation

A second set of suggestions concerned making information easier to understand once found. The most common request was for plain language: writing at an accessible level, explaining or avoiding jargon, and not assuming the reader has prior expertise.

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Respondents also asked for more context – where and how the information can be applied – and for a clearer explanation of the models, methods, and parameters behind it, including guidance on reading maps and models. More accessible summaries were requested, including short overviews, summaries for policymakers, summaries in both Dutch and English, and syntheses of the current state of knowledge on a topic. Visual presentation was again mentioned as an aid to understanding.

The same need surfaced in the sharing question, where respondents noted that effective sharing required bridging the gap between technical content and audiences with limited background knowledge while preserving the necessary nuance. One respondent emphasized the difficulty of this by noting that even informed parties can misjudge risks, such as overestimating the impact of geothermal drilling on groundwater.

3.5.3 Metadata and standardization

Across all three questions, respondents repeatedly raised the need for better documentation and more consistent data. Many wanted clear information on how, when, and by whom data were produced, with their uncertainties stated, so that the data can be interpreted and reused with confidence. The same concern reappeared in the sharing question: for information to be useful to other organizations, it must not only be released but also documented well enough to be found and understood.

Closely related was a call for standardization: uniform formats, metadata, coordinate systems, and naming conventions. One respondent set out in detail how data standards often fail in practice, through inconsistent naming, ambiguous coordinate systems, and incomplete lineage (i.e., tracking how data are produced, modified, transmitted, and applied across systems with time). As a solution, the respondent proposed that platforms such as NLOG enforce validation and quality control before data are published.

3.5.4 Sharing and inter-organizational exchange

Several suggestions addressed sharing specifically between organizations. Respondents noted that preparing data for external use, translating it for non-experts, and publishing datasets all take time and effort that current workloads and reward structures do not account for. Many called for more coordination and shared infrastructure across the sector because such structures would enable sharing, but are currently missing or underdeveloped: e.g., coordinated oversight of the entire information chain, from the national registry (i.e., BRO) through government bodies to the requesting end user. One respondent named GeoKennisNL as a possible coordinating body. Opportunities and a willingness to engage were also raised: one respondent asked for more opportunities for knowledge exchange among academia, industry, and government, while others described a lack of interest in cross-organizational exchange as the main obstacle. Respondents also framed openness as a matter of policy, calling for mandatory open-access publication, the publication of operators' regional studies, and legal obligations on companies to share their survey data.

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3.5.5 Transparency and framing

A final, smaller set of responses concerned how subsurface information was presented, and by whom. Some respondents wanted the interests of the organization producing a document to be made visible, so that readers can weigh the information in light of who produced it and why. Others argued that the portrayal of the subsurface should change. After a decade in which the public narrative has centered on risks, several felt it was time to give equal weight to the opportunities, particularly given the subsurface's central role in the energy transition.

3.6 Preferred future tools and formats

When asked which of a set of proposed tools they would be likely to use, respondents most strongly endorsed an integrated national knowledge database (87.7%), consistent with the demand for a single access point raised in the open-ended responses. An overview map of research and networks, as well as regular knowledge days and sector events, also received moderate-to-high endorsement. Sector newsletters, interactive future-scenario tools, and short video explainers formed a second cluster, endorsed by around one in three. Online training modules, cheat sheets, an ask-an-expert service, and standardized Q&A/FAQ materials were endorsed least, though still by roughly a fifth to a quarter of respondents. Full frequencies are reported in ***Table* 3**.

Two stakeholder differences emerged: regional and local governments were more likely to endorse standardized Q&A/FAQ materials and online training modules or webinars, while university respondents were less likely to endorse Q&A/FAQ materials (***Table B 1***). Under "other," one respondent noted that it is more important to promote awareness of existing tools rather than create new ones.

4 Discussion

A major lesson from the Groningen gas production and the physical, economic, and societal damage that followed was that information about subsurface activities and their risks needs to be transparent, accessible, and independently verifiable. The establishment of GeoKennisNL in 2025, a national program to coordinate, develop, and share subsurface knowledge, signals that policymakers are taking this lesson to heart. However, strengthening the knowledge infrastructure requires knowing in what ways findability, comprehensibility, and information sharing currently fall short.

This study set out to answer that question by surveying professionals working on subsurface issues across domains. By capturing demand and supply side by side, across seven stakeholder groups (research institutes, universities, national government bodies, regional and local governments, advisory bodies, industry, and consultancy and engineering), we traced not only what information professionals need and use, but also what they share, and where the two sides diverge. In the next sections, we summarize the results and then provide an integrated discussion of the findings, their limitations, and implications.

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4.1 Summary of the results

With 135 respondents from more than 55 organizations, the study captured a good breadth of the Dutch subsurface sector, though national government bodies were overrepresented and civil society was severely underrepresented. Respondents were experienced with subsurface issues and frequently sought information, so the difficulties they reported cannot be attributed to inexperience. In response to the first research question, respondents sought information across a wide range of topics (most often subsurface geology, geothermal energy, and induced seismicity) primarily to assess risk and conduct research. Both topics and purposes differed across groups in ways that aligned with organizational mandates: academic actors were oriented toward research and geological data, industry and consultancy toward applied project purposes, regional and local governments toward permitting, spatial planning, and shallow-subsurface topics, and national government bodies toward resource-related topics, specifically oil and gas, and public communication.

Regarding the second research question, respondents did not perceive finding and understanding information as particularly difficult, yet they still reported a range of barriers to both. Finding information was hampered above all by fragmentation across sources, and further by poor usability and interoperability, restricted access, and a lack of location-specific detail; understanding it was impaired mainly by poorly explained models and assumptions. Stakeholder differences in specific barriers were sparse. National government bodies more often reported insufficient time to search, likely reflecting that their staff have less room for prolonged searches than, for instance, researchers working on the same topic for years. Universities and research institutes cited a foreign-language barrier more often, probably for opposing reasons: universities employ more foreign staff who might struggle with Dutch-language policies and industry reports, while research institutes are more Dutch-speaking environments, where the predominantly English-language scientific literature might produce comprehension difficulties. Even where respondents named missing topics (e.g., stress maps, fault-rock properties, or permit records; **Table 4**), the data often existed but in the wrong form: what was generally missing was information sufficiently detailed, synthesized, current, or boundary-spanning (i.e., across borders, from surface to subsurface, and across time) to support decision-making.

Respondents most frequently consulted knowledge institutions (research institutes, advisory bodies, and universities) and public digital platforms, followed by gray and academic literature, as well as sector events such as conferences. (Environmental) NGOs, community organizations, and newer channels such as social media and AI tools were used least. Most respondents also shared information themselves, predominantly technical data and research outputs, through in-person events and formal reports. However, bilateral sharing and digital platforms were also frequently used.

Both consumption and sharing followed an in-group pattern in which respondents drew on and shared with organizations closest to their own roles: regional and local governments turned more often to provincial and municipal sources, universities relied more on academic literature, and advisory bodies drew more on gray literature and internal documents, likely because their work depends more heavily on reports than that of other stakeholders. Information was shared mostly within respondents' own organizations, followed by industry, national government bodies, and academic organizations, with little to no sharing with community organizations and (environmental) NGOs. Intellectual property or commercial sensitivity and limited time

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were the main barriers to sharing, and stakeholder differences again reflected mandates, answering the third research question on sharing constraints. Organizational culture, by contrast, was generally not perceived as a barrier to information sharing. When asked where exchanges should increase, respondents generally wished to exchange more with research institutes and the national government bodies, though universities wanted more exchanges with the general public.

Turning to the fourth research question, respondents rated information providers moderately positively on all quality dimensions, with knowledge institutions rated highest on clarity, transparency, competence, and trustworthiness, and commercial, local government, and civil society sources rated lower. Regarding information characteristics, reliability and transparency about uncertainty were valued most; independence of the provider, comparability and consistency, and up-to-dateness were also considered important, whereas clear explanations of policy and decision implications and understandability for non-specialists or the public were rated only moderately important. The results tentatively suggested, however, that regional and local governments place more weight on information being understandable to non-specialists, possibly because staff at decentralized government bodies have less specialized subsurface expertise than industry and academic respondents.

Respondents encountered epistemic uncertainty, arising from insufficient knowledge or data, more often than aleatory uncertainty, arising from natural geological variability. Answering the fifth research question, they expressed a strong preference for transparent communication of uncertainty, believed it serves the public by conveying the full picture and informing judgment, and worked in organizations that expect them to communicate uncertainty. Preferred formats were best estimates plus numeric ranges, visualizations, scenarios with descriptions, and percentile formats. However, they also reported that the information they receive explains uncertainty too rarely and that their organizations offer limited guidance on how to communicate it.

In the open-ended responses, respondents converged on a desire to consolidate, standardize, and better document subsurface information, with almost unanimous support for an integrated national knowledge database. Across all findings, four consistent themes emerged, which we discuss next: fragmentation, in-group information flows, uncertainty transparency, and trust deficits.

4.2 Cross-cutting themes

4.2.1 Fragmentation is the sector's central and shared problem

Subsurface information in the Netherlands is fragmented, and our respondents experience this as a sector-wide problem. Fragmentation across sources was by far the most cited barrier to finding information, well above any other, and one of the issues on which stakeholder groups did not differ: academics, government, industry, and consultancy alike struggle to assemble a complete picture from scattered sources. The same concern ran through the open-ended responses, where the most common suggestion was to bring subsurface information together in one place, and through the tool preferences, where an integrated national knowledge database received the most support. Information could often not be found because it was released without the documentation needed to make it findable. In response, respondents broadly demanded information consolidation.

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What our respondents describe differs from the Groningen case in that information is dispersed across many providers, rather than concentrated within a few. Still, it has similarly negative consequences: no actor can readily assemble the coherent, reliable overview that safe and effective subsurface governance requires. Some respondents also specify what consolidation should look like: rather than a repository that just holds data, it should be standardized and organized around its purpose. A central platform will therefore properly address fragmentation only if it also invests in curation, metadata, and standardization.

4.2.2 Information flows follow an in-group pattern

Information in the sector moves in line with professional similarity. Respondents mainly consulted and shared with the organizations most closely aligned with their roles and responsibilities. The groups on the edge of the sector, (environmental) NGOs and community organizations, were consulted the least and shared with the least. The general public was rarely named as an audience at all (except by universities). This is consistent with Rodrigues et al.'s (2025) finding that geoscientists' outreach concentrates on students, teachers, and fellow researchers while rarely reaching NGOs or local communities. It also reflects the weakness exposed in Groningen, where knowledge circulated within a closed network, and independent or dissenting voices struggled to be heard (Tweede Kamer, 2023). The sector we surveyed is broader and more open than that network at the time, but the information still flows mostly within clusters and barely across them, and least of all toward civil society stakeholders.

When asked which organizations they would prioritize for increased exchange, respondents mostly pointed to research institutes and national government bodies, the actors already at the center of the network, rather than to peripheral groups. Universities' wish for more exchange with the general public was the notable exception here. In other words, the sector's own stated priorities would, if followed, largely reinforce the existing structure rather than open it up. This is concerning because (environmental) NGOs and community groups play an important role in representing public interests in debates over subsurface activities. The implication is that the extension of information to civil society and the public needs to be actively supported.

4.2.3 Professionals value uncertainty transparency, but they struggle to provide it

Another challenge concerns how uncertain information is communicated. Respondents consistently valued transparency about uncertainty. They rated it among the most important characteristics of information, expressed a strong personal preference for learning about uncertain findings, and reported that their organizations expect them to communicate such findings rather than simplify or omit them. Yet they also reported that the information they receive explains uncertainty too rarely, and that their organizations give them little guidance on how to communicate it. There is a mismatch between how much uncertainty is valued and how well it is currently communicated.

This gap should be taken seriously because the broader evidence suggests that transparency about uncertainty is less risky than communicators often assume, provided it is done well. Disclosing uncertainty numerically, such as a range around a point estimate, generally does not reduce trust in the information or its source, whereas vaguer verbal expressions (e.g., "it could be

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somewhat higher or lower") are more likely to (van der Bles et al., 2020). Beyond trust, quantification improves people's understanding of low-probability risks (Knoblauch et al., 2018), and technical uncertainty (i.e., quantified error ranges and probabilities) rarely has negative effects, whereas communicating expert disagreement tends to undermine audience confidence (Gustafson and Rice, 2020). It also matters how probabilities are phrased, with positively framed (e.g., "a low probability of severe drought") and numerically anchored expressions (e.g., “a 5-8% chance of severe drought”) conveying stronger evidence than negative ones (e.g., “severe drought is unlikely”) (Juanchich et al., 2025). Audiences also differ in how much uncertainty they want to learn about, depending on factors such as scientific understanding and trust in science (Ratcliff et al., 2023).

Our respondents' format preferences largely align with this evidence. They favored a best estimate with a numeric range, visualizations, multiple scenarios, and percentiles over vaguer qualitative terms. This suggests that respondents already value transparency and roughly know what good uncertainty communication looks like, but lack the guidance to produce it consistently. Practical support, such as guidance on formats and terminology (van der Bles et al., 2020; Erharter et al., 2024; Juanchich et al., 2025), would help address the sector's struggle with uncertainty communication.

4.2.4 Trust concentrates in knowledge institutions

Respondents rated the organizations whose information they used, and a clear hierarchy emerged. Knowledge institutions, namely research institutes, universities, and advisory bodies, were rated highest on clarity, transparency, competence, and trust. Commercial, local government, and civil society sources were rated lower, and trust in regulators varied more widely than in any other source.

Longitudinal research in Groningen found that the acceptability of subsurface activities depends on both the perceived competence and, more strongly, the perceived integrity of the responsible organization, that is, whether it is seen to care about local impacts and to be transparent about risks (Liu et al., 2022). The sources our respondents rated lowest are, plausibly, those most exposed on one or both counts: commercial operators on integrity (here, transparency), given their stake in the outcome of subsurface decisions, and local governments and civil society bodies on competence, given more limited subsurface expertise. The lower clarity and transparency ratings for industry stakeholders in this study could, in turn, negatively affect their social license to operate in the Netherlands. The more variable levels of trust in regulators could reflect mistrust regulators have faced since the Groningen controversy.

The sources most trusted are already central to the sector's information flows, while several of those less trusted, particularly local government and civil society bodies, sit on its edge. Efforts to broaden participation, therefore, run up against a trust deficit: the actors that a more inclusive information system would need to draw in are, on average, the ones respondents currently rate lower on competence, transparency, and trust. Whether such negative perceptions are the cause or the result of a lack of exposure to these information providers cannot be determined from our cross-sectional data.

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4.3 Limitations and future research directions

Several limitations should be kept in mind when interpreting these findings. Respondents self-selected into the survey, and recruitment was more effective within organizations to which we had existing ties. National government bodies were overrepresented, civil society was almost absent (n = 2), and several stakeholder groups had small cell sizes even after regrouping (e.g., sector associations combined with industry; environmental protection agencies combined with regional and local governments). The lack of civil society respondents is consistent with our finding that this group sits at the edge of the subsurface information system, but it also limits what we can say about that group's information needs and practices.

We conducted a substantial number of inferential group comparisons, with Bonferroni correction applied only within pairwise follow-ups, not across item families. Pattern-level findings should therefore be weighted more heavily than significant results on any single item. The cross-sectional design further precludes causal inference about the relationships we describe, such as whether fragmentation drives in-group information flows or vice versa, or whether limited exposure to peripheral information providers shapes lower trust in them or vice versa.

The Dutch subsurface sector has several distinctive features that may limit the transferability of these findings. The Dutch governance structure is unusually dense, with multiple overlapping institutions, advisory bodies, and knowledge programs operating within a small national territory. The Groningen gas controversy and the parliamentary inquiry that followed have made information governance a politically charged topic, likely heightening respondents' awareness of trust and transparency issues in ways that would not apply in countries without a comparable experience. Even after the termination of gas production in Groningen, politicized conflicts over compensation for building damage and regional redevelopment projects linger. While the underlying challenges of subsurface inaccessibility, inherent uncertainty, and information fragmentation are probably shared across countries with active subsurface sectors, the specific institutional and political conditions documented here should be considered when interpreting these results for other contexts.

All findings rely on self-reports and lack behavioral or observational validation. Respondents may over- or underreport barriers, sharing practices, or difficulty ratings due to social desirability or recall effects. Our shortened version of the PIUS-11 scale showed acceptable internal consistency but does not measure the construct as originally validated; comparisons with studies using the full scale should be made with caution. Finally, the Dutch survey translation was prepared by the first author and reviewed by a native speaker from the field, but a full back-translation procedure was not conducted; the effect of wording differences between the language versions cannot be entirely ruled out.

Several of these limitations point to avenues for future research. The lack of civil society stakeholders in our sample means that their perspective on the subsurface information system remains understudied. Research with NGOs and community organizations (e.g., through targeted interviews or focus groups) could clarify what information these groups seek, where they struggle, and why they occupy such a peripheral position. Our cross-sectional data likewise cannot establish whether low trust in information providers drives limited exposure, or whether limited exposure produces low trust through unfamiliarity. Longitudinal designs, or experimental work manipulating exposure to peripheral information sources, could help untangle the

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direction of the relationship. The Dutch-specific scope of our findings invites comparable studies in other national contexts to test whether fragmentation and in-group patterns are inherent features of subsurface sectors or specific to the Dutch context. Finally, GeoKennisNL is now being established as a national program to improve the coordination, development, and sharing of subsurface knowledge. The present findings offer a baseline against which future work can measure whether consolidation, curation, and standardization actually change fragmentation, in-group information flows, and trust patterns over time.

5 Conclusions

This study investigated how subsurface information flows among Dutch professionals and where it falls short. The findings from 135 respondents across more than 55 organizations indicate that stakeholders do not find it extraordinarily difficult to locate, understand, and share information. However, there is still substantial room for improvement in the existing information exchange. The available information is highly fragmented, making it hard to assemble a coherent and reliable picture of the subsurface. Information typically moves among organizations with overlapping mandates and responsibilities, while (environmental) NGOs and community organizations, in particular, are disconnected from the rest of the sector. While the sector generally values transparent communication of uncertainty, it is inconsistently practiced and poorly taught. Finally, trust is concentrated in knowledge institutions and is especially lacking for peripheral actors such as (environmental) NGOs and community organizations.

Four priorities for policy and practice follow from these findings. First, building an integrated national platform that invests not only in access, but also in curation, metadata, and standardization. Second, creating incentives and cultivating a culture that extends information flows toward civil society actors. Third, providing sector-wide guidance and training on communicating uncertainty. Fourth, improving transparency measures for sources perceived as less credible, particularly the industry, for instance, by making the assumptions, methods, and interests behind their information transparent to other stakeholders. These priorities require the kind of sustained, cross-sector coordination that a national body like GeoKennisNL could provide. Acting jointly on these priorities would address the sector's problems at their root and support the safe and effective use of the subsurface.

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Appendix A

Table A 1
Names of the Organizations that Respondents Reported Working for, Organized by Sector and Type

Sector	Organization type	Organization name
Government	National government	• Central Organization for Radioactive Waste (COVRA) • Energie Beheer Nederland (EBN) • Ministry of Climate Policy and Green Growth (KGG) • Ministry of Economic Affairs and Climate (EZK) • Ministry of Infrastructure and Water Management (I&W)
	Regulatory and advisory bodies	• Advisory Group for Economic Affairs (TNO-AGE) • Geological Survey Netherlands (TNO-GDN) • Groningen Safety Advisory Board (ACVG) • Mining council (Mijnraad)
	Regional and local government	• Environmental protection agencies (Flevoland & Gooi en Vechtstreek; Haaglanden; Rijnmond; Utrecht; Zuid-Holland; Zuid-Limburg; Zuidoost-Brabant) • Municipalities (Utrecht; Velsen) • National Coordinator Groningen (NCG) • Provinces (Drenthe; Fryslân; Groningen; Noord-Brabant)
Research	Universities	• Delft University of Technology • Kiel University • Open University • University of Groningen • University of Twente • Utrecht University • Vrije Universiteit Amsterdam
	Research institutes	• Deltares • Netherlands Organisation for Applied Scientific Research (TNO) • Royal Netherlands Meteorological Institute (KNMI)
	Public research programmes	• Knowledge Programme Mining Effects (KEM)

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Sector	Organization type	Organization name
Industry	Consultancy	• Bodemkundig Adviesbureau Edelman • dGB Earth Sciences • Fugro • IWSS • PanTerra Geoconsultants • Seequent • Sproule ERCE
	Developers and operators	• Gaia Energy • Heijmans Energie / HeZon • Kon. Heijmans NV • NAM • Nobian • Recoal AG • Wintershall Noordzee BV
	Sector and trade associations	• Geothermie Nederland • Glastuinbouw Nederland • Vewin
Other		• Energy Innovation NL (TKI) Urban Energy • Mobilization for the Environment • Rabobank • Stichting Risswerk

Note. Disclosing one's organizational affiliation was optional; therefore, not all the organizations represented in the survey are listed.

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Appendix B

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Fisher-Freeman-Halton Exact Test Results for Stakeholder Group Differences in Search Frequency, Topics Sought, Purposes, Barriers, Information Types Shared, Audiences, Exchange Priorities, Sharing Methods, Uncertainty Types, and Preferred Uncertainty Formats and Tools

Item	Test statistic	*p*	Stakeholder group pattern
Search frequency (n=129)	35.227	.070	-
Topics (n=130)			
Subsurface geology and geophysical interpretation	24.559	**<.001**	RI, CON overrepresented; RL underrepresented
Geothermal energy	12.060	.059	-
Induced seismicity or subsidence	9.313	.159	-
Geological modeling	13.251	**.038**	CON overrepresented; RL underrepresented
Oil and gas resources	20.669	**.002**	RI, NG overrepresented; UNI underrepresented
Energy storage	17.584	**.007**	RI, UNI overrepresented; RL underrepresented
Salt mining	9.033	.159	-
Underground infrastructure (cables, pipelines, etc.)	3.066	.819	-
Mining impacts	7.399	.283	-
Shallow subsurface	17.596	**.006**	RI, RL overrepresented; UNI underrepresented
Groundwater	7.472	.284	-
Underground thermal energy storage	9.815	.125	-
Soil/groundwater contamination and remediation	34.467	**<.001**	RL overrepresented; NG underrepresented
Cross-cutting or general subsurface topics	15.692	**.014**	UNI underrepresented
Purposes (n=130)			
Risk assessment or preventive risk mitigation	1.919	.948	-
Scientific research	58.826	**<.001**	UNI, RI overrepresented; IND, RL underrepresented

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Item	Test statistic	*p*	Stakeholder group pattern
Project design or feasibility studies	31.828	**<.001**	IND, CON overrepresented; UNI, RL underrepresented
Public communication or stakeholder engagement	18.084	**.006**	NG overrepresented; CON underrepresented
Preparing or evaluating permit applications	19.875	**.002**	RL overrepresented; UNI underrepresented
Developing policies or regulations	23.782	**<.001**	RL overrepresented; UNI underrepresented
Spatial planning or area development	26.966	**<.001**	RL overrepresented; UNI underrepresented
Field or reservoir development	18.271	**.002**	CON overrepresented; RL underrepresented
Informing investment or business decisions	25.401	**<.001**	CON overrepresented; UNI underrepresented
Geotechnical investigation	18.814	**.002**	CON overrepresented; RL underrepresented
Education or training	10.543	.093	-
Operational management	5.800	.413	-
Decommissioning	8.711	.127	-
Regulatory supervision or enforcement	10.083	.071	-
Developing subsidies	6.477	.261	-
Damage claims or incident response	8.242	.133	-
Barriers to finding information (n=128-130)			
Fragmentation across sources	1.008	.992	-
Not available in a usable or interoperable format	4.955	.556	-
Not publicly available	1.617	.966	-
Too few local or site-specific details	3.047	.819	-
Barely been collected	6.921	.313	-
Behind paywalls or otherwise restricted	5.107	.525	-
Insufficient time to search	15.908	**.007**	NG overrepresented
Difficulty judging reliable sources	8.061	.180	-
Unclear where to look or which search terms to use	2.583	.883	-

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Item	**Test statistic**	***p***	**Stakeholder group pattern**
Language barrier	11.260	**.005**	UNI, RI overrepresented
Barriers to understanding information			
Underlying models/assumptions poorly explained	11.755	.063	-
Too little explanation or context in general	3.398	.780	-
Too much jargon	7.018	.312	-
Technically too complex	4.810	.567	-
Too much detail	6.383	.375	-
Contradictions between sources	12.141	**.039**	RI overrepresented
Visualizations (maps/graphs) hard to interpret	4.919	.563	-
Difficulty translating information into one's own work	3.400	.784	-
Foreign language	9.137	.039	RI overrepresented
Information types shared (n=90)			
Policy or strategy documents (e.g., ministerial strategy papers)	15.321	**.007**	RL overrepresented; UNI underrepresented
Laws, regulations, or guidelines	3.312	.800	-
Permit and license applications	22.420	**<.001**	IND, CON overrepresented; UNI, RI underrepresented
Regulatory or compliance reports (e.g., production report)	4.897	.452	-
Advice on policy or permitting	21.658	**<.001**	RL overrepresented; UNI underrepresented
Technical/geological data or models	24.319	**<.001**	UNI overrepresented; RL underrepresented
Project designs or feasibility studies	21.629	**<.001**	CON overrepresented; UNI underrepresented
Data on field or reservoir development	6.480	.358	-
Gas/oil well design information	10.517	**.022**	IND overrepresented
Scientific research outputs	43.055	**<.001**	UNI, RI, ADV overrepresented; IND, RL underrepresented
Environmental or social impact assessment	3.527	.763	-
Operational monitoring reports	8.785	.145	-

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Item	Test statistic	*p*	Stakeholder group pattern
Risk or safety assessments	5.531	.486	-
Damage assessment or compensation documents	4.254	.764	-
Public communication or outreach materials	6.451	.375	-
Educational or training materials	14.443	**.017**	UNI overrepresented; RL underrepresented
Audiences for shared information (n=90)			
Internal colleagues/management	10.299	.064	-
National government bodies	31.669	**<.001**	RI, ADV, NG, RL overrepresented; UNI underrepresented
Regulators and enforcement bodies	18.060	**.003**	RI, ADV overrepresented; UNI, RL underrepresented
Advisory bodies	32.783	**<.001**	RI, ADV overrepresented; UNI, RL underrepresented
Provinces	31.629	**<.001**	RL overrepresented; UNI, IND underrepresented
Municipalities	26.602	**<.001**	RL overrepresented; UNI, IND underrepresented
Industry and commercial operators	7.066	.320	-
Sector or trade associations	3.274	.802	-
(Inter)national research community	32.208	**<.001**	UNI, ADV overrepresented; NG, RL underrepresented
Specific scientific or academic organizations	30.965	**<.001**	UNI overrepresented; IND, CON, RL underrepresented
Priorities for improved information exchange (n=120)			
National government bodies	10.630	.086	-
Regulators and enforcement bodies	5.464	.489	-
Advisory bodies	6.476	.362	-
Provinces	4.667	.591	-
Municipalities	9.461	.122	-
Water boards	2.659	.908	-
Industry and commercial stakeholders	7.037	.301	-

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Item	**Test statistic**	***p***	**Stakeholder group pattern**
Sector and trade associations	4.180	.660	-
Dutch research institutes	8.604	.182	-
Dutch universities and academic groups	6.967	.296	-
International research community	12.703	**.008**	ADV overrepresented
(Environmental) NGOs	3.911	.838	-
Community groups and local residents	4.622	.575	-
General public	13.168	**.026**	UNI overrepresented
Sharing methods (n=90)			
Digital platforms and repositories	14.088	**.024**	RI, ADV overrepresented
Formal reports or publications	39.021	**<.001**	UNI, ADV overrepresented; IND, RL underrepresented
Organizational websites or press releases	15.149	**.015**	ADV overrepresented; IND underrepresented
Social media or newsletters	7.255	.295	-
Conferences, workshops, professional meet-ups	26.213	**<.001**	ADV overrepresented; IND, RL underrepresented
Public submission to a regulator/governmental agency	11.541	**.040**	IND overrepresented; UNI underrepresented
Confidential submission to a regulator/governmental agency	15.354	**.011**	IND overrepresented; UNI underrepresented
Direct sharing with specific stakeholders	10.963	.090	-
Upload to the internal project or the data drive	7.740	.263	-
Sharing barriers (n=90)			
Legal or regulatory restrictions	8.898	.168	-
Intellectual property or commercial sensitivity	8.754	.176	-
Organizational culture discourages sharing	5.895	.287	-
Lack of time or capacity	7.429	.271	-
Lack of a clear mandate or responsibility	4.032	.700	-
Slow internal approval processes	9.942	.075	-
Information not in an easily shareable format	20.983	**<.001**	RL overrepresented; NG underrepresented

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Item	**Test statistic**	***p***	**Stakeholder group pattern**
Lack of suitable sharing platforms/systems	1.332	.993	-
Data quality insufficient for sharing	9.673	.089	-
Difficulty translating information for non-specialists	4.494	.636	-
Uncertainty about the relevant audience	5.891	.407	-
Lack of feedback on the usefulness of shared information	8.068	.131	-
Uncertainty experienced (n=120)			
Epistemic uncertainty	10.946	.051	-
Aleatoric uncertainty	3.516	.755	-
None	4.200	.588	-
Preferred uncertainty formats (n=120)			
Single best estimate without explicit uncertainty	2.021	.977	-
Best estimate plus qualitative term	5.782	.402	-
Best estimate plus numeric range	9.996	.160	-
Explicit probability or return period statements	9.229	.159	-
Visual depiction	8.896	.179	-
Multiple scenarios with descriptions	14.706	**.022**	RI overrepresented; IND, CON underrepresented
Percentile formats	16.094	**.013**	ADV, NG overrepresented
Organizational norms			
Preferred tools and formats (n=117)			
National knowledge database	8.175	.160	-
Sector newsletter	8.506	.198	-
Map of research (networks)	5.619	.465	-
Public helpdesk	2.016	.935	-
Scenario explorer tool	7.178	.302	-
Explanatory videos	4.536	.612	-
Knowledge days/sector events	3.756	.724	-

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Item	Test statistic	*p*	Stakeholder group pattern
Standardized Q&A/FAQ materials	12.507	**.036**	RL overrepresented; UNI underrepresented
Online training modules or webinars	13.951	**.024**	RL overrepresented
Fact sheets	8.789	.179	-

Note. The stakeholder group pattern column reports the direction of significant findings as explained in the results section. P-values significant at the .05-level are bolded.
Group abbreviations: CON = consultancy and engineering; IND = industry; NG = national government bodies; RI = research institutes; RL = regional and local governments; UNI = universities.

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Table B 2

Kruskal-Wallis Test Results for Stakeholder Group Differences in Difficulty, Source Consultation, Channel Use, Information Quality and Needs, Organizational Uncertainty Norms, Preference for Uncertainty, Uncertainty Effects, and Explanations

Item	***N***	***H***	***df***	***p***	**Significant pairwise differences**
Difficulty finding information	128	7.184	6	.304	-
Difficulty understanding information	127	7.054	6	.316	-
Sources					
Research institutes	127	28.688	6	**< .001**	ADV > RL, NG, IND, UNI; RI > RL
Advisory bodies	126	24.826	6	**< .001**	ADV > RL, UNI
National government bodies	126	19.079	6	**.004**	NG > RI, CON, RL
Provinces	125	37.815	6	**< .001**	RL > all other groups
Municipalities	124	28.158	6	**< .001**	RL > UNI, IND, NG, RI
Universities	125	33.622	6	**< .001**	UNI > RL, NG, IND, CON
Industry	125	6.483	6	.371	-
Regulators and enforcement bodies	127	8.685	6	.192	-
Sector or trade associations	126	.613	6	.996	-
(Environmental) NGOs	126	2.165	6	.904	-
Community organizations	126	8.202	6	.224	-
Channels					
Public digital platforms or repositories	127	10.868	6	.093	-
Peer-reviewed literature	127	46.649	6	**< .001**	UNI > RL, IND, NG; RL < CON, IND, RI, ADV
Gray literature or technical reports	127	18.390	6	**.005**	ADV > IND
Organizational websites or press releases	127	4.505	6	.609	-
Social media or newsletters	127	8.530	6	.202	-
Conferences, workshops, professional meet-ups	127	9.158	6	.165	-
Internal documents or information	126	22.716	6	**< .001**	UNI < NG, ADV
AI language models or domain-specific AI tools	127	15.052	6	**.020**	(no pair survived correction)
Quality of information					

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Item	***N***	***H***	***df***	***p***	**Significant pairwise differences**
Coverage	127	8.869	6	.181	-
Up-to-dateness	127	4.010	6	.675	-
Reliability	127	3.050	6	.803	-
Clarity	127	4.126	6	.660	-
Ease of access	127	8.256	6	.220	-
Information needs					
Up-to-dateness	117	6.248	6	.396	-
Reliability	117	7.980	6	.240	-
Transparency about uncertainty	117	6.228	6	.398	-
Independence of provider	117	7.640	6	.266	-
Comparability and consistency	117	9.679	6	.139	-
Clear policy/decision implications	117	8.836	6	.183	-
Understandability for non-specialists/public	117	12.757	6	**.047**	(no pair survived correction)
Organizational uncertainty norms					
Expectation to communicate transparently	89	9.023	6	.172	-
Expectation to avoid confusion	88	3.580	6	.733	-
Expectation to avoid controversy	86	8.540	6	.201	-
Adequate guidance for communication	87	6.577	6	.362	-
Preference for learning about uncertainty	119	6.785	6	.341	-
Perceived uncertainty effects (n=125)					
Realistic public expectation	120	13.508	6	**.036**	ADV > RI
Improved informed judgments	120	7.317	6	.293	-
Decreased public trust	120	8.330	6	.215	-
Decreased public support	120	5.017	6	.542	-
Uncertainty sufficiently explained	109	5.469	6	.485	-

Note. Significant pairwise differences are based on Bonferroni-adjusted pairwise comparisons ($p < .05$) and are reported as "Group A > Group B."
730 P-values significant at the .05-level are bolded.

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Group abbreviations: ADV = advisory bodies; CON = consultancy and engineering; IND = industry; NG = national government bodies; RI = research institutes; RL = regional and local governments; UNI = universities.
For the AI tools channel, the omnibus test was significant, but no individual pairwise comparison passed the Bonferroni correction.

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Table B 3

Repeated-Measures ANOVA Results for Within-Sample Differences in Source and Channel Use, Information Quality, and Importance Characteristics (Greenhouse-Geisser Correction)

Item	***F***	***df1***	***df2***	***p***	***partial η²***	**Significant pairwise differences**
Sources	65.023	5.947	755.315	**< .001**	.339	RI, ADV > REG, NG, PRV, MUN, IND, SEC, NGO, COM; RI > UNI; UNI > REG, PRV, MUN, IND, SEC; NG > PRV, MUN; NGO, COM < all others
Channels	64.079	5.141	668.271	**< .001**	.330	DIG > all others; PEER, GRAY, INT, EVT mutually ns (GRAY > EVT); WEB < PEER, GRAY, INT; SOC, AI < all others, except each other
Information quality	5.700	3.718	487.070	**< .001**	.042	RE > UTD, EA
Importance characteristics	26.510	3.932	475.737	**< .001**	.180	RE > TR, IDP, UTD, COMP, POL; TR > UTD, COMP, POL; IDP > POL; UND < all others

Note. P-values significant at the .05-level are bolded.

Abbreviations sources: ADV = advisory bodies; COM = community organizations; CON = consultancy and engineering; IND = industry; MUN = municipality; NG = national government bodies; NGO = (Environmental) NGOs; PRV = provinces; REG = regulators; RI = research institutes; SEC = sector associations; UNI = universities.

Abbreviations channels: AI = AI tools; DIG = public digital platforms and repositories; EVT = conferences, workshops, and professional meet-ups; GRAY = gray literature; INT = internal documents; PEER = peer-reviewed literature; SOC = social media/newsletters; WEB = organizational websites.

Abbreviations information quality/needs: RE = reliability; UTD = up-to-dateness; EA = ease of access; TR = transparency; IDP = independence of provider; COMP = comparability; POL = policy and decision implications; UND = understandability for non-specialists/public

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Table B 4
Mean Values of Clarity, Transparency, Competence, and Trust Ratings

Item	*M*	*SD*	Verbal label
Clarity of information (n = 21-114)			
Research institutes (e.g., TNO, KNMI, PBL)	4.15	0.598	Agree
National government (e.g., RVO, EZK, EBN)	4.04	0.766	Agree
Advisory bodies (e.g., Mijnraad, TNO-GDN)	4.03	0.766	Agree
Sector and industry associations	3.96	0.706	Neither nor – agree
Universities and academic groups	3.84	0.842	Neither nor – agree
Regulators and enforcement bodies (e.g., SodM)	3.67	0.798	Neither nor – agree
Community organizations	3.67	0.796	Neither nor – agree
(Environmental) NGOs	3.65	0.714	Neither nor – agree
Industry (incl. operators)	3.57	0.718	Neither nor – agree
Provinces	3.49	0.727	Neither nor
Municipalities	3.46	0.711	Neither nor
Transparency about methods/limitations (n = 21-109)			
Universities and academic groups	4.26	0.754	Agree
Research institutes (e.g., TNO, KNMI, PBL)	4.10	0.881	Agree
National government (e.g., RVO, EZK, EBN)	3.95	0.922	Neither nor – agree
Advisory bodies (e.g., Mijnraad, TNO-GDN)	3.90	0.891	Neither nor – agree
Regulators and enforcement bodies (e.g., SodM)	3.48	0.911	Neither nor
Sector and industry associations	3.31	0.755	Neither nor
Provinces	3.26	0.902	Neither nor
(Environmental) NGOs	3.18	0.795	Neither nor
Municipalities	3.11	0.953	Neither nor
Industry (incl. operators)	3.05	0.753	Neither nor
Community organizations	3.05	0.865	Neither nor
Perceived competence (n = 22-110)			
Research institutes (e.g., TNO, KNMI, PBL)	4.42	0.709	Agree
Advisory bodies (e.g., Mijnraad, TNO-GDN)	4.34	0.685	Agree
Universities and academic groups	4.33	0.758	Agree
National government (e.g., RVO, EZK, EBN)	4.05	0.742	Agree
Industry (incl. operators)	3.84	0.768	Neither nor – agree
Sector and industry associations	3.79	0.825	Neither nor – agree
Regulators and enforcement bodies (e.g., SodM)	3.71	0.830	Neither nor – agree
Provinces	3.40	0.728	Neither nor
(Environmental) NGOs	3.27	0.550	Neither nor

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Item	*M*	*SD*	Verbal label
Municipalities	3.15	0.933	Neither nor
Community organizations	3.00	0.756	Neither nor
Trust in information (n = 22-110)			
Research institutes (e.g., TNO, KNMI, PBL)	4.39	0.718	Agree
Universities and academic groups	4.38	0.739	Agree
Advisory bodies (e.g., Mijnraad, TNO-GDN)	4.31	0.775	Agree
National government (e.g., RVO, EZK, EBN)	4.17	0.768	Agree
Regulators and enforcement bodies (e.g., SodM)	3.76	1.016	Neither nor – agree
Sector and industry associations	3.68	0.850	Neither nor – agree
Provinces	3.64	0.685	Neither nor – agree
Industry (incl. operators)	3.56	0.794	Neither nor – agree
Municipalities	3.46	0.897	Neither nor
(Environmental) NGOs	3.27	0.703	Neither nor
Community organizations	3.13	0.869	Neither nor

Note. Items were rated on 5-point scales: 1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, 5 = strongly agree. Verbal labels correspond to the nearest scale anchor or anchor interval for each mean.

Data availability

The underlying research data can be accessed at https://data.4tu.nl/private_datasets/RQ_3O3WjK6X1Yyl2LxvAAJtRHFw1OzjXwU142E8U5v8 *[Note: this is a pre-view link; the proper link will be provided once the manuscript has been accepted for publication and the dataset has been published].*

Author contributions

Helena Schmidt: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. Gerdien de Vries: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. Aad Correljé: Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Competing interests

The authors declare no conflicts of interest.

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Ethical statement

Ethics approval was granted by TU Delft's Human Research Ethics Committee (approval reference: 6411). Respondents read an informed consent statement on the first page of the survey outlining data management practices, voluntary participation, and the anonymous handling of their survey responses, and provided consent by clicking through to the survey start page. Data were stored and handled in compliance with the GDPR. Contact details for the lottery were collected separately from survey responses and deleted after the winners were informed.

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