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Interdisciplinary Pathway for Sustainable Management of Geological Resources: A Case Study in Flanders

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ABSTRACT

The subsurface is often overlooked in sustainable natural resource management, despite its vital geosystem services — supporting, provisioning, regulating, and cultural — and its role in energy storage and geothermal energy for a sustainable future. Presently, subsurface use follows a first-come-first-served model, often resulting in inefficiencies and inequities. As demand increases, sustainable development policies become essential. Six key challenges have been identified: value pluralism, overexploitation, geological interferences, inequalities, multi-actor economies, and uncertainties. Addressing these requires interdisciplinary collaboration, which enhances creativity and problem-solving but also introduces challenges like conflicting viewpoints, disciplinary assumptions, and knowledge gaps. We present ongoing work from the DIAMONDS project, that proposes a framework — the DIAMONDS elevator — for effective interdisciplinary collaboration in sustainable subsurface development. We detail methods to integrate diverse expertise and tackle the outlined challenges. The framework includes building interdisciplinary teams, developing integrative strategies, and applying stakeholder-validated case studies. Our research is further enhanced through stakeholder mapping and engagement, ensuring inclusive representation. Collaboration is supported by targeted management practices within the project and with external stakeholders, tailored to their expertise — ranging from technical interviews to workshops on equitable resource ownership. Synthesized insights are derived from flexible, cross-disciplinary tools like causal loop diagrams, which map interactions within the subsurface system. The framework is applied to a stakeholder-validated case study on potentially interacting shallow subsurface activities: aquifer thermal energy storage and groundwater extraction. This paper presents the interdisciplinary approach and specific methods applied in the case study.

1 INTRODUCTION

The subsurface is a vital component of our environment, supplying essential resources such as fuels, minerals, groundwater, and heat, while also serving as a space for energy and CO_2 storage and nuclear waste disposal (Hermans et al., 2023). Despite its critical importance, the public remains largely unaware of how deeply modern society depends on subsurface resources. Historically, exploration and exploitation were driven by those who first claimed it, often neglecting broader environmental and societal implications. However, as demands increase, unregulated or competing uses of the subsurface threaten efficiency, safety, and environmental integrity, making sustainable management an urgent priority (Compernolle et al., 2023), especially in the context of the energy transition and decarbonization efforts.

Achieving sustainability in subsurface management is a complex challenge due to overlapping geological and administrative boundaries and competing stakeholder interests. Compernolle et al. (2023) identified six major challenges: 1) integrating value pluralism, 2) defining sustainable scales of use, 3) evaluating interferences, 4) ensuring environmental justice, 5) optimizing efficiency, and 6) managing uncertainties. Addressing these requires an interdisciplinary approach that integrates knowledge from multiple disciplines simultaneously. While many studies have recognized this need, most research either focuses on one activity through multiple disciplinary lenses or examines multiple activities from a single disciplinary viewpoint, revealing a need for more integrated frameworks.

Recent studies illustrate both disciplinary depth and interdisciplinary potential. For instance, Elshall et al. (2020) promoted a transdisciplinary framework for groundwater management, and Guglielmetti et al. (2025) applied spatial multi-criteria analysis to assess High-Temperature ATES potential. Techno-economic studies, such as those by Daniilidis et al. (2022) and Chen et al. (2018), have explored the cost-efficiency of individual subsurface

uses, while others propose incorporating “geosystem services” into economic assessments. In social sciences, attention is shifting from project-specific analyses toward justice-oriented approaches that address inequalities in subsurface interventions, e.g: Caballero et al. (2024) for groundwater; Towers & Cotton (2024) for nuclear waste management; Swennenhuis et al. (2022) for carbon capture and storage (CCS); and Parson et al.(2025) for geothermal energy. Meanwhile, geology and engineering research continue to focus on optimizing technologies and reducing conflicts between co-located systems.

Despite valuable advances, a significant research gap remains: few studies integrate geological, economic, and social perspectives to assess interactions between multiple subsurface activities. A notable exception is a Flemish government-commissioned study (Compernolle et al., 2023), which modeled such interferences and inspired the DIAMONDS project. This initiative advances a comprehensive interdisciplinary framework—the DIAMONDS Elevator—for sustainable subsurface management. By fostering collaboration across disciplines, it aims to clarify complex subsurface interactions and guide sustainable governance. The framework is demonstrated through a Flemish case study examining the interplay between ATES and groundwater extraction, highlighting how structured interdisciplinary methods can support informed decision-making and sustainable development of the subsurface.

2 BUILDING AN INTERDISCIPLINARY TEAM

Building an effective interdisciplinary team marks the essential first step toward achieving sustainable subsurface management, as outlined by Compernolle et al. (2023). The key disciplines contributing to this endeavour are geology and subsurface or reservoir engineering, economics, environmental sciences, and sociology. Geology provides the foundation for understanding subsurface systems, offering critical insights into spatial and temporal scales that extend far beyond human experience. Geological knowledge enables the identification and assessment of resources, evaluation of risks, and management of uncertainty (Challenge 6: handling uncertainties), while also informing the sustainable scale of use (Challenge 2: sustainable scale). The inherent variability and uncertainty of subsurface conditions require geoscientists to employ a combination of direct and indirect methods to interpret hidden properties, facilitating collaboration with other disciplines to address interferences between subsurface activities (Challenge 3: evaluating interference).

Economics plays a central role in assessing the feasibility and efficiency of subsurface projects. Economic analysis determines whether projects yield positive long-term returns and helps balance financial viability with sustainability goals. This is achieved by quantifying costs, revenues, and potential interferences (Challenge 3), improving economic efficiency (Challenge 5: optimizing environmental and economic efficiency) and supporting decision-making under uncertainty (Challenge 6: handling uncertainties). It also identifies how costs and benefits are distributed among investors, communities, and other stakeholders, intersecting with issues of environmental justice (Challenge 4: environmental justice). However, traditional economic approaches must be expanded to include ecological and social boundaries through ecological economics, ensuring that externalities such as environmental damage are internalized. Moreover, economics offers insights into competitive behaviour among investors, highlighting the need for governance structures that integrate value pluralism (Challenge 1: value pluralism) and define sustainable thresholds for subsurface use (Challenge 2: sustainable scale).

Environmental sciences broaden the scope of sustainability assessments by examining ecological impacts beyond climate change mitigation. Tools such as Life Cycle Assessment (LCA) enable systematic evaluation of environmental trade-offs across the full life cycle of technologies and processes (Hauschild et al., 2018), thereby supporting the optimization of environmental and economic efficiency (Challenge 5: optimizing environmental and economic efficiency). However, LCA alone cannot capture the full ecological complexity of subsurface systems, which interact closely with geo- and ecosystems (Stemmle et al., 2021). Technologies like geothermal energy or ATES can both enhance sustainability and pose environmental risks, such as thermal or ecosystem pollution (Blum et al., 2021). These effects influence public perception and environmental justice (Challenge 4: environmental justice), as communities exposed to higher risks may resist projects perceived as unfair.

From a sociological perspective, sustainable subsurface management entails addressing justice, participation, and intergenerational responsibility. Sociologists examine how the benefits and burdens of subsurface activities are distributed across communities, questioning who gains and who bears the risks (du Pisani & Sandham, 2006; Schlosberg, 2013). This focus on distributive and procedural justice supports environmental justice (Challenge 4: environmental justice) and highlights the social dimensions of uncertainty (Challenge 6: handling uncertainty). Sociological research also emphasizes participatory decision-making, transparency, and stakeholder engagement as prerequisites for social acceptance and trust (Barich et al., 2022). Projects that are technically and economically viable may still fail without local support, illustrating the need to integrate value pluralism (Challenge 1: value pluralism) in governance. Beyond these core disciplines, law, policy, political science,

ethics, and spatial planning provide critical perspectives on rights, responsibilities, and institutional dynamics. Their inclusion enriches interdisciplinary collaboration, helping to navigate the regulatory, ethical, and spatial complexities of an increasingly crowded and contested subsurface.

3 CASE STUDY

Once an interdisciplinary team is established, the challenging task of managing multiple users and uses of the subsurface can be systematically addressed. Within the DIAMONDS project, the multifunctional use of the subsurface in Flanders is explored using the DIAMONDS-Elevator—a framework designed to support interdisciplinary collaboration and information exchange across different decision-making levels, from policy and planning to operations and evaluation. To demonstrate its application, a case study on Aquifer Thermal Energy Storage (ATES) and groundwater extraction illustrates how this framework structures and communicates assumptions, findings, and interactions between disciplines, ultimately enabling coordinated management of concurrent subsurface activities.

In Flanders, the multifunctional use of the subsurface is particularly complex due to limited available space and an intricate policy environment. Groundwater extraction, a long-established source of drinking water, relies on sustainable withdrawal rates that do not exceed aquifer recharge. Meanwhile, ATES systems offer an emerging solution for seasonal energy storage, providing heating and cooling through the subsurface. However, as both activities target the same aquifers, they may interfere with each other—pressure gradients from groundwater extraction can shift thermal plumes, and ATES-induced temperature changes may affect groundwater quality. Current Flemish subsurface policy, based on a “First Come, First Served” principle, prioritizes existing uses like drinking water production, restricting newer technologies such as ATES. While this precautionary approach protects groundwater resources, it also hinders integrated management. To move toward sustainable subsurface governance, both activities must be jointly evaluated to understand and mitigate potential interferences while balancing the broader energy and water needs.

4 FRAMEWORK FOR THE INTEGRATION OF DISCIPLINES

True interdisciplinarity extends beyond assembling experts, it requires integrating diverse methods, perspectives, and knowledge systems. The DIAMONDS Elevator serves as a framework for linking disciplines across interconnected decision-making levels, from policy to evaluation (Figure 1). These include developing a shared language to overcome disciplinary silos, engaging in perspective taking to challenge assumptions and stimulate creativity, and creating common ground through shared frameworks such as systems thinking or environmental justice. Regular consortium meetings, peer-to-peer exchanges, and advisory sessions with stakeholders ensure that the resulting framework remains both scientifically rigorous and societally relevant.

To support decision-making across the Elevator, DIAMONDS employs integrative tools that structure interdisciplinary insights. The Principles, Criteria & Indicators (PC&I) framework translates the six sustainability challenges identified by Compernolle et al. (2023) into measurable criteria and indicators, ensuring that decisions at all levels remain aligned with ecological and social boundaries. Causal Loop Diagrams (CLDs) enable researchers to map system dynamics across technical, social, and environmental domains, revealing feedbacks and interdependencies often missed in disciplinary isolation. Multi-Criteria Decision Analysis (MCDA) helps navigate value pluralism by integrating qualitative and quantitative criteria across disciplines, fostering transparent and participatory decision-making. Together, these tools guide the decision-maker from structuring principles (PC&I) to identifying interactions (CLDs) and ranking options (MCDA).

At the planning level (Level 1), geological models and dynamic simulations form the foundation for understanding subsurface conditions and predicting responses to human interventions. Participatory data collection complements these technical analyses by capturing stakeholder knowledge, perceptions, and concerns. These dialogues feed directly into interdisciplinary tools such as CLDs and the PC&I framework, ensuring that planning decisions reflect both scientific understanding and social legitimacy. At the operational level (Level 2), Techno-Economic Assessment (TEA) connects geological and technical parameters to economic feasibility, translating system performance into financial outcomes and guiding design optimization.

At the evaluation level (Level 3), we use Real Options Analysis (ROA), Life Cycle Assessment (LCA), and Game Theory to enable comprehensive assessment of uncertainty, sustainability, and interaction between multiple actors. ROA incorporates flexibility and uncertainty into investment decisions, while LCA quantifies the environmental impacts of technologies across their life cycles. Game theory models strategic interactions among stakeholders competing for shared subsurface resources, highlighting potential conflicts and cooperative solutions. Insights from these evaluations feed back into earlier levels, ensuring adaptive and informed management of subsurface resources.

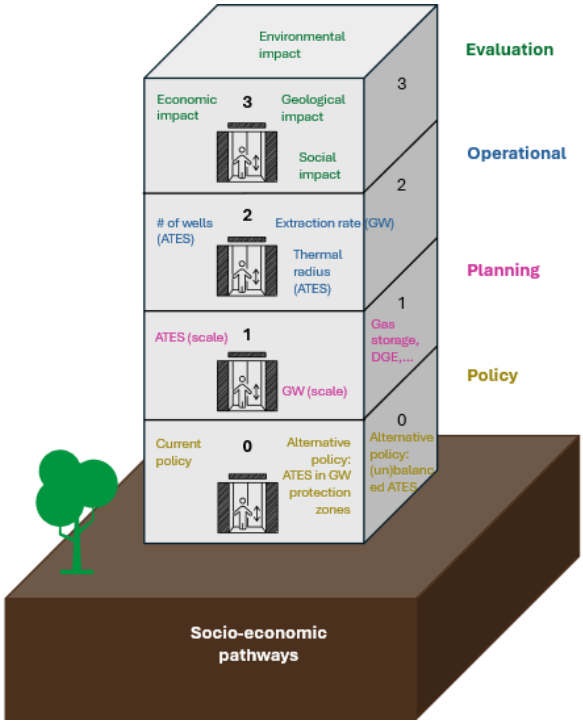


Figure 1. An example of the possible options, choices or types at each level of the DIAMONDS Elevator, for the case of ATES and groundwater (GW) extraction specifically.

By integrating these methods across the Elevator, DIAMONDS provides a structured yet flexible framework for sustainable subsurface governance. The combined use of PC&I, CLD, MCDA, TEA, ROA, and LCA ensures that geological, technical, economic, environmental, and social dimensions are coherently linked. This approach enables decision-makers to identify trade-offs, anticipate interferences, and balance competing interests across levels of policy and practice. Ultimately, the DIAMONDS framework demonstrates how structured interdisciplinarity can transform complex, fragmented understandings of the subsurface into coherent strategies that support long-term sustainability and equitable resource use.

5 CONCLUSIONS

The integration framework within DIAMONDS shows that achieving true interdisciplinarity goes beyond coordination—it requires continuous translation, negotiation, and synthesis across disciplinary boundaries. Through structured mechanisms like the DIAMONDS Elevator and reflexive practices such as shared language development, perspective taking, and creation of common ground, the project models how diverse expertise can align toward shared sustainability goals. This integrative process transforms isolated insights into coherent, multi-level understanding, enabling decision-makers to navigate complexity while respecting ecological limits and societal values.

The Elevator's suite of tools—PC&I, geological models and dynamic simulations, CLD, MCDA, TEA, ROA, and LCA—forms the operational backbone for interdisciplinary decision-making. Each occupies a distinct role within the vertical structure, yet together they create a feedback-rich network that bridges policy, planning, operational, and evaluation levels. By balancing structure with flexibility, the framework allows exploration of trade-offs, testing of scenarios, and adaptation as knowledge evolves. In doing so, DIAMONDS transcends static assessment, fostering adaptive governance grounded in systems thinking and participatory engagement. This approach demonstrates that sustainable subsurface management depends not on disciplinary excellence alone but on weaving technical, economic, environmental, and social dimensions into a collective, iterative process—offering a replicable model for addressing complex socio-technical challenges in the Anthropocene.

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