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Underground Hydrogen Storage in Island Settings: Integrating Groundwater Vulnerability and Supply into Early-Stage Site Selection

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Summary

With Canada demonstrating an interest in decarbonizing remote communities, rapid renewable energy penetration in isolated grids will increase the need for resilient seasonal energy storage infrastructure to maintain system stability. Underground hydrogen storage (UHS) is increasingly considered a large-volume and long-duration storage option in such contexts. However, its applicability depends on both the local energy system and the presence of suitable geological settings. In communities where favourable conditions coexist, such as the Magdalen Islands (Quebec) where diapiric salt structures may enable salt-cavern storage, UHS merits early-stage evaluation. Yet, many preliminary UHS screening frameworks are driven primarily by geological and infrastructure criteria, while hydrogeological constraints are commonly treated as secondary. The importance of these constraints is amplified in island environments, where drinkable water resources often depend on scarce freshwater lenses hydraulically connected to seawater and are therefore sensitive to contamination and pumping-induced salinization. This contribution synthesizes recent hydrogeological studies from the Magdalen Islands and translates them into a UHS-relevant screening approach that integrates freshwater supply reliability and groundwater protection into early salt-cavern siting. Spatial indicators of vulnerability and salinization risk are combined with freshwater availability metrics in a multi-criteria workflow to prioritize investigation areas and identify influential parameters (e.g., aquifer exploitation potential, depth to the freshwater-saltwater interface, DRASTIC vulnerability index, recharge areas, and fault proximity). Paired with conventional geological and technical constraints, the resulting outputs support clearer early-stage planning and orient future UHS screening toward preliminary assessments that explicitly reflect (i) reliable freshwater supply and (ii) aquifer protection requirements. Applied to the Magdalen Islands, the hydrogeology-informed screening introduces 7% additional exclusion area and reduces the extent of high-scoring classes (scores 7-8) by 24 and 63% respectively, highlighting that groundwater constraints can considerably affect high suitability sectors' area at the regional screening stage.

Theory / Method / Workflow

The Magdalen Islands are a small, remote archipelago in the Gulf of St. Lawrence whose electricity supply has historically relied on imported fossil fuels. Their local geology is characterized by sedimentary units overlying major Windsor Group salt diapirs in the Maritimes Basin (Brisebois, 1981), motivating an assessment of coupling wind-farm expansion with underground hydrogen storage (UHS) in salt caverns. This study builds on work conducted under the Quebec groundwater knowledge acquisition projects (PACES), and in particular the hydrogeological synthesis for the Magdalen Islands by Lemieux et al. (2022), which constrains groundwater resources and vulnerability. By applying these findings to an underground hydrogen storage (UHS) site-selection exercise initially driven by technical and geological criteria, the study

demonstrates how island hydrogeology introduces first-order constraints that can shift early siting outcomes.

Freshwater demand associated with hydrogen production is treated here as a site compatibility issue rather than a detailed supply-design exercise. Municipal pumping provides an order-of-magnitude benchmark for safe aquifer use on the archipelago, with reported average pumping rates ranging from ~75 to 300 m^3/day per municipal well on the main distribution networks and lower per-well rates in smaller systems (Lemieux et al., 2025). Under freshwater-lens conditions, feasibility is expected to depend less on annual pumped volume totals than on well placement, interference with existing well fields, and pumping-induced salinization risk (Coulon et al., 2022). To reduce net groundwater demand, product water from hydrogen conversion may be recovered and recirculated for electrolysis with reported recovery fractions spanning roughly 40-80% depending on technology and condensation strategy, although condenser costs may only be justified in strongly water-limited settings (Tibaquirá et al., 2011; Zakhvatkin et al., 2022). Alternatively, reinjection of recovered water could contribute to locally limiting saltwater intrusion by sustaining a positive hydraulic barrier (Pool & Carrera, 2010). Exhaust-water management remains a key design consideration but is not modelled here and is retained for discussion.

Cavern creation is also out of scope. Development is assumed technically adaptable to island conditions without drawing on freshwater lenses, for example via seawater-based solution mining with offshore brine disposal (Ahmad & Baddour, 2014; Field et al., 2019).

While a fully revised hydrogeological model of the study area is also beyond scope, screening requires an optimized limited set of decision-relevant parameters. Criteria weights were informed through interviews with site-specific technical experts and implemented in a weighted-sum suitability framework. For operational clarity, hydrogeological criteria are grouped into: (1) aquifer exploitation, guiding the placement of freshwater supply wells while minimizing interference and salinization risk, and (2) aquifer protection, constraining cavern and surface-facility siting to reduce exposure of vulnerable groundwater resources. The two groups are normalized to 100% for decision support, with group-level weights summarized in Figure 1. Criteria considered qualitatively contradictory across groups (e.g., shoreline proximity and municipal well density) were excluded from the quantitative screening.

This GIS-based multi-criteria workflow integrates freshwater supply and groundwater protection constraints into early-stage salt-cavern screening, alongside conventional geological and technical criteria. Hydrogeological criteria capture both: (1) aquifer exploitation feasibility and freshwater-lens sensitivity by integrating the depth of the freshwater-saltwater interface, as well as (2) aquifer protection-oriented indicators (via the DRASTIC vulnerability index (Aller et al., 1987), recharge contribution areas, and structurally controlled potential leakage pathways through fault proximity). Regulatory and operational exclusion zones derived from well protection constraints are also applied (Figure 1). The technical criteria evaluate proximity to existing electrical infrastructure, zoning and slopes, while geological criteria evaluate surface geology, depth-to-salt from seismic interpretations, as well as gravimetric and magnetic aerial survey data.

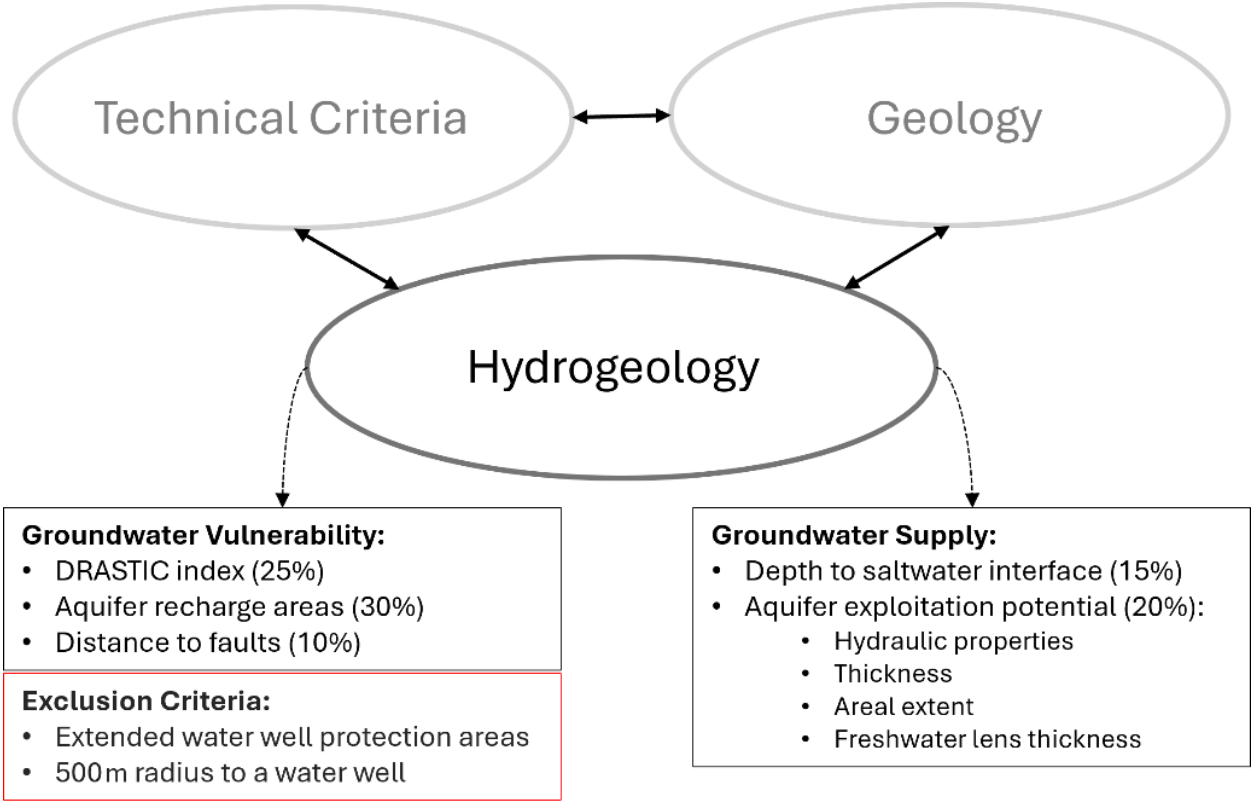


Figure 1. Criteria categories, datasets and exclusion criteria influencing the hydrogeological suitability for UHS site selection. Relative criteria weights for the base scenario are in parentheses.

Results, Observations, Conclusions

At the regional scale of the Magdalen Islands, integrating hydrogeological supply and protection constraints modifies the spatial pattern of preliminary UHS favorability compared to geology- and infrastructure-dominated screening alone (Figure 2). By adding 7% of the total exclusion zone area and lowering the area of suitability value scores of 7 and 8 by 24 and 63% respectively (Table 1), integrating hydrogeological criteria in site selection reduces the high suitability area surface considerably. The aquifer recharge area has proven to be the most sensitive parameter based on its sensitivity index (SI) score, followed by aquifer exploitation potential and DRASTIC Index. Their accurate characterization is therefore critical to an optimized preliminary assessment.

While suitability score outputs are intended as screening-level prioritization and exclusion guidance rather than final site selection, adding hydrogeological criteria based on quality data has demonstrated that this criterion category integration is critical for a robust preliminary assessment. The resulting investigation-priority zones provide a defensible basis for targeting subsequent field characterization and for identifying which hydrogeological parameters and uncertainties should be constrained first to improve early decision-making.

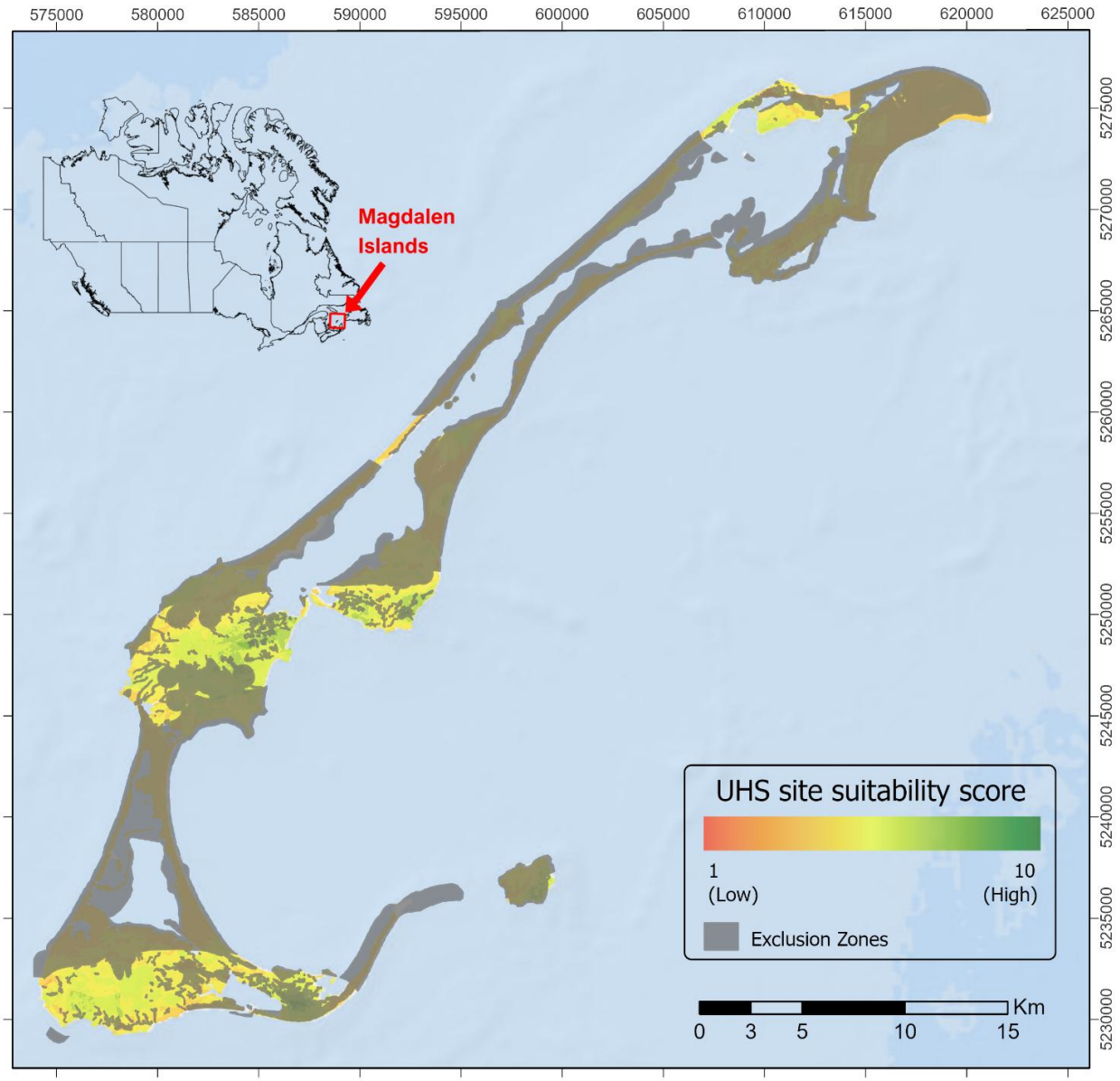


Figure 2. Map of the integrated underground hydrogen storage (UHS) site suitability score for the Magdalen Islands area when integrating hydrogeological criteria to the site selection spatial multi-criteria analysis

Table 1. Comparative table of UHS suitability score by area units of 625 m^2 (25 m x 25 m) based on technical & geological (1) criteria vs. integrating hydrogeological criteria (2).

		UHS suitability score (1-10)										Exclusion Zones
		(Low)									(High)	
		1	2	3	4	5	6	7	8	9	10	
Scenario	1	0	0	177,58	113,960	98,410	65,058	14,963	2,721	2	0	283,573
	2	0	4	1,610	121,789	113,372	63,689	11,414	994	0	0	304,350
Difference (units)		**0**	**4**	**-16,148**	**7,829**	**14,962**	**-1,369**	**-3,549**	**-1,727**	**-2**	**0**	**20,777**
Difference (%)		-	-	-91%	7%	15%	-2%	-24%	-63%	-	-	7%

Novel/Additive Information

This contribution advances early UHS screening by translating island-aquifer hydrogeological knowledge into a UHS-specific, GIS-based decision workflow that treats freshwater supply reliability and groundwater protection as first-order siting constraints. By explicitly accounting for freshwater-lens sensitivity to pumping-induced salinization (upconing), the approach provides a structured way to reconcile salt cavern UHS opportunities with documented freshwater resource management realities in the Magdalen Islands. While developed for an insular salt-cavern case study, the framework is transferable to other groundwater-scarce settings where hydrogeology can meaningfully constrain, exclude, or re-rank candidate zones during preliminary UHS planning.

Acknowledgements

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