Infrastructure Resilience Against Climate Change Challenges in Quebec

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ABSTRACT
Land subsidence associated with groundwater pumping, once primarily considered a concern for large developing megacities, is now recognized as a global geotechnical issue. Sustained declines in pore-water pressures lead to irreversible compaction of aquifers and aquitards, resulting in progressive ground deformation and damage to surface infrastructure.
In Québec, despite abundant groundwater resources and a well-established regulatory framework, climate change is altering the regional water balance by reducing natural recharge and extending summer drought periods. This trend increases reliance on groundwater, particularly in rural and agricultural areas, and may heighten the risk of geotechnical settlement in compressible clay–silt deposits.
This study highlights the importance of integrated water–soil–infrastructure management to reduce settlement and subsidence risks associated with groundwater drawdown, which may affect the service life, functionality, and structural integrity of existing structures and infrastructure.

RÉSUMÉ
Le tassement des sols lié au pompage des eaux souterraines, longtemps perçu comme un enjeu propre aux grandes mégapoles en développement, est désormais reconnu comme une problématique géotechnique à l'échelle mondiale. La baisse prolongée des pressions interstitielles entraîne une compaction irréversible des aquifères et des aquitards, provoquant des déformations progressives du sol et des dommages aux infrastructures de surface.
Au Québec, malgré une ressource en eau abondante et un cadre réglementaire bien établi, les changements climatiques modifient le bilan hydrique régional en réduisant la recharge naturelle et en prolongeant les périodes de sécheresse estivale. Cette tendance accroît le recours aux eaux souterraines, notamment en milieux rural et agricole, et augmente le risque de tassement dans les dépôts argilo-silteux compressibles.
Cette étude souligne l'importance d'une gestion intégrée de l'eau, du sol et des infrastructures afin de limiter les risques de tassement et d'affaissement liés à l'abaissement des nappes, susceptibles d'affecter la durée de vie, la fonctionnalité et l'intégrité structurale des ouvrages existants.

1. INTRODUCTION

1.1 Context and motivation

Groundwater resources are essential for municipal water supply, agricultural irrigation, and industrial activities. However, sustained groundwater extraction can lead to significant geotechnical impacts, most notably land subsidence resulting from the compaction of aquifers and aquitards. Although this phenomenon has been widely documented in large, densely urbanized, and rapidly developing regions, it is increasingly recognized as a pervasive issue in temperate regions characterized by extensive deposits of compressible soils.

Land subsidence induced by groundwater pumping is primarily driven by reductions in pore-water pressure, which increases effective stress within soil deposits and triggers irreversible deformation—particularly within clayey and silty aquitards. The resulting ground surface settlements typically develop gradually and may remain undetected over long periods. Nevertheless, these deformations can have significant adverse effects on the structural performance, serviceability, and long-term durability of buildings and civil infrastructure.

In Québec, groundwater has traditionally been perceived as a resilient and abundant resource, a perception that has historically limited concern regarding long-term drawdown and associated geomechanical effects. However, groundwater use is spatially heterogeneous and increasingly concentrated in the St. Lawrence Lowlands, where most of the population and critical infrastructure are located. In this region, significant groundwater exploitation leads to localized alterations of hydraulic gradients and sustained declines in groundwater levels.

Consequently, despite generally favorable recharge conditions at the provincial scale, the interaction between pumping, climate-driven recharge reduction, and geotechnical vulnerability raises concerns about long-term settlement and subsidence risks in parts of southern Québec where groundwater use is intensive and infrastructure density is high.

1.2 Objective and scope of the study

Québec regulatory framework focuses primarily on water quality protection and drinking-water source safeguarding. Consideration of geotechnical consequences such as settlement or land subsidence associated with long-term groundwater drawdown is generally indirect and not explicitly addressed within groundwater management regulations.

Therefore, the main objective of this paper is to underscore the need for an integrated water−soil−infrastructure framework—combining hydrology, hydrogeology, geotechnics, and climatology—to inform regulatory frameworks, improve groundwater management, and mitigate settlement and land subsidence risks, as well as their impacts on existing structures and civil infrastructure.

The scope of the study is regional and focuses on sensitive clay-dominated zones in southern Québec, including the St. Lawrence Lowlands. The analysis emphasizes long-term trends and cumulative effects rather than short-term or localized pumping scenarios.

Figure 1 presents a conceptual workflow illustrating how climate-change-driven hydroclimatic trends, groundwater conditions, and regional subsurface characteristics are integrated to frame the assessment of soil and infrastructure vulnerability addressed in this study.

1.3 Methodological approach

This study is based on the consultation and synthesis of existing hydrogeological, geological, geotechnical, and climatic data to support a regional-scale vulnerability assessment in Québec. The approach relies exclusively on publicly available data sources and does not involve the reprocessing of raw datasets, including the following:

- Groundwater conditions are documented using monitoring records from the Québec Groundwater Monitoring Network (RSESQ).
- Geological and hydrostratigraphic information is drawn from mapping products produced by Ministère des Ressources naturelles et des Forêts (MRNF) and the *Institut national de la recherche scientifique* (INRS), identifying aquifers, aquitards, and compressible clay-rich units.
- Climate-related information is based on Horizon 2050 projections and published regional studies concerning precipitation, evapotranspiration, recharge, and drought conditions.

The assessment also considers the spatial overlap between compressible clay-rich deposits and existing infrastructure. In southern Québec, particularly within the St. Lawrence Lowlands, these geotechnically sensitive settings are prone to consolidation under long-term groundwater level declines, increasing the potential for total and differential settlements and associated impacts on infrastructure performance (Shafaei Shahboulaghi et al., 2025).

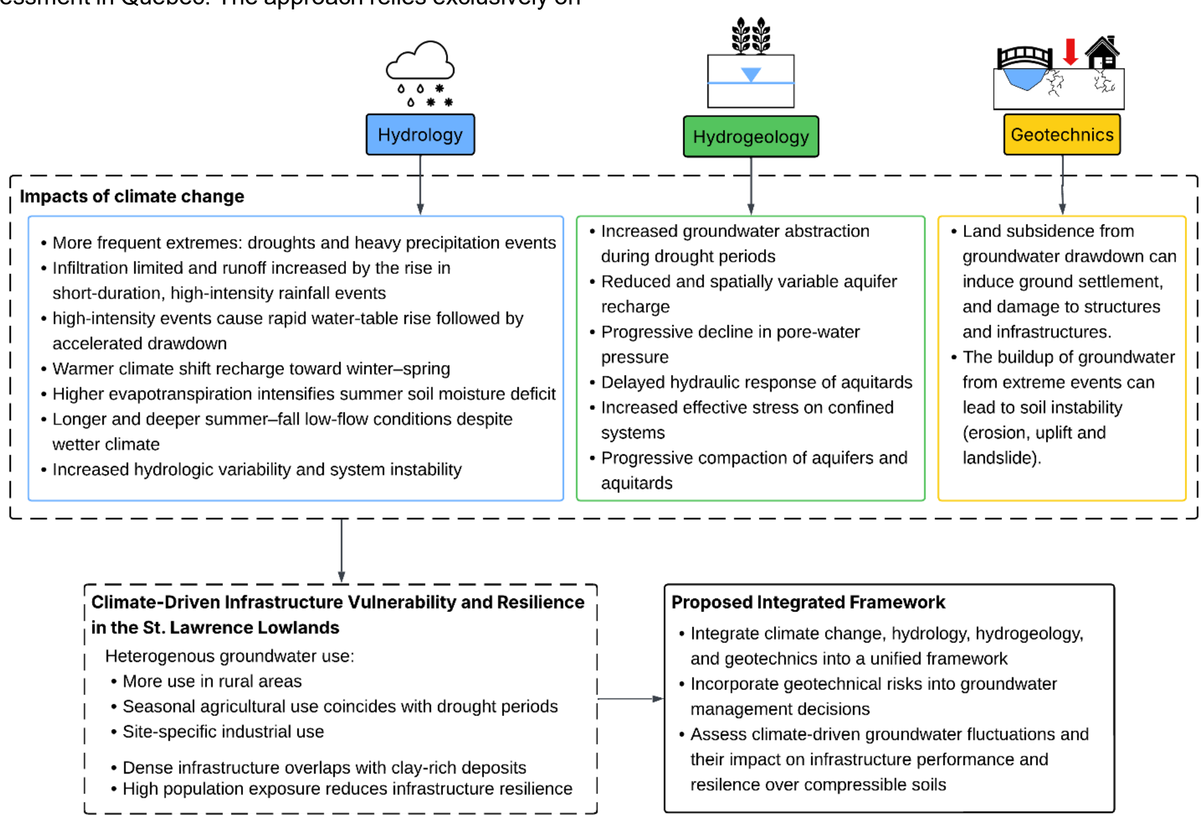

Figure 1. Conceptual workflow for climate-change-driven groundwater–soil–infrastructure assessment

1.4 Structure of the paper

The paper is organized as follows. Section 2 presents background information on the geology of Québec, regional climate change trends, and the groundwater regulatory framework. Section 3 discusses climate change and its implications for the water balance in Québec. Section 4 describes the hydrogeological setting, including aquifer and aquitard characteristics and groundwater exploitation patterns. Section 5 focuses on geotechnical considerations, detailing settlement and subsidence mechanisms associated with groundwater drawdown.

Section 6 discusses infrastructure resilience, vulnerability, and potential mitigation strategies in the context of climate change. Finally, Section 7 summarizes the main findings and outlines directions for future research.

2 BACKGROUND

2.1 Geology of Québec

There are nine distinct geological provinces in Quebec, but only four of these are found in the south of the province: the Grenville Province, the St. Lawrence Platform, the Appalachian Province and the Monteregian Hills.

The St. Lawrence Platform is located along the south and north shores of the St. Lawrence River, stretching from southwestern Quebec (the Outaouais and Gatineau areas) to Quebec City (MRNF, 2023). It is also referred to as the St Lawrence lowlands due to its flat topography and low elevation (less than 100 m) (Ministère de l'Environnement, lutte contre les changements climatiques, Faune et Parcs (MELCCFP), 2026b). The St. Lawrence Platform consists of sedimentary rocks dating from 550 to 475 million years ago (Government of Québec, 2025) which are covered by thick glacial, littoral, and marine deposits (from the Champlain sea), sometimes reaching over 170 m in depth (MELCCFP, 2026b; Russell et al., 2011). Out of all four geological provinces in the south of Quebec, the St Lawrence Platform is the most densely populated—with about 4 million inhabitants (MELCCFP, 2026b).

The Monteregian Hills are a series of 120 to 140 million-year-old intrusive rock mountains that stretch from Saint-André (north-west of Montreal) to Mont Mégantic (east of Sherbrooke) in the St. Lawrence Platform and Appalachian Province (Government of Québec, 2025).

To the north of the St Lawrence Platform is the Grenville Province: an ancient, deformed mountain chain made of metamorphic rock (Government of Québec, 2025). It is approximately 350 km wide and 2000 km long along the SW-NE axis (MRNF, 2018) and has an elevation ranging from 600 to 1000 m (MELCCFP, 2026c). The rocks of the Grenville Province are some of the oldest on the planet, with some specimens being over 2.5 billion years old (MRNF, 2018).

The Appalachian Province, located to the south of St Lawrence Platform, is estimated to be between 450 and 290 million years old (MELCCFP, 2026a). It is composed of an ancient sedimentary oceanic crust and ultramafic rock (Government of Québec, 2025) with elevations reaching 1200 m in the north-east, over Gaspé (MELCCFP, 2026a).

2.2 Overview of climate change in Québec

Between 1948 and 2012, the mean annual total precipitation in southern Quebec increased by 5 to 15 % due to climate change. The average increase across the province was higher in spring and fall (+20 %), and lower in winter and summer (+5 %). In addition, the proportion of precipitation falling as rainfall, as well as the number of days with intense rainfall recorded, also increased between 1948 and 2012 (Ouranos, 2022).

Quebec is often considered a water-abundant region because spring snowmelt replenishes groundwater and sustains streamflow, limiting the occurrence of prolonged droughts (Assani, 2023). However, recent decades show increasing vulnerability to drought conditions, with some areas currently (March 2026) classified as Moderate to Severe Drought according to the Canadian Drought Monitor (Government of Canada, 2026). Hydrological drought impacts both surface and underground water resources and occurs when rivers, streams, and other water bodies experience significant reductions in flow or water levels (Ouranos, 2024c). One third of gauged hydrometric stations in southern Quebec show that current summer and fall low flows are longer-lasting and more severe than in 1970. This phenomenon primarily affects southern Quebec. However, during the spring and winter seasons, 40 % of the stations actually show less severe low flows than in 1970 in southern Quebec (Ouranos, 2024a).

2.3 Groundwater regulatory framework and use in Québec

Groundwater in Québec is considered a public resource and is governed by the provincial environmental legal framework. Its management and protection are under the responsibility of the MELCCFP, with geological and hydrogeological information support provided by the MRNF.

Groundwater withdrawals are regulated under the *Loi sur la qualité de l'environnement (LQE)* and its associated regulations, notably the *Règlement sur l'Encadrement d'Activités en Fonction de leur Impact sur l'Environnement (REAFIE)*, which defines the conditions under which water withdrawals, including the abstraction of groundwater, require ministerial authorization. In this context, some groundwater-related activities may be exempted from ministerial authorization or may fall under simplified administrative procedures, depending on the applicable thresholds and conditions. Québec also maintains the *Réseau de suivi des eaux souterraines du Québec (RSESQ)*, a province-wide monitoring network with more than 270 active observation wells distributed across all regions of the province, the vast majority of which are located below 50° North (MELCCFP, 2026e).

Groundwater use in Québec is spatially heterogeneous, reflecting regional differences in water availability, infrastructure, land use, and economic activity. While some municipalities rely primarily on surface sources for their water supply, the majority (90 %) of the inhabited territory of Quebec relies on groundwater sources for their supply, including municipalities, rural communities, agricultural areas, and industrial facilities. Furthermore, 25 % of the population (over two million people) relies on groundwater sources for their drinking water, as less densely populated areas rely more on groundwater sources (MELCCFP, 2026d; Ministère du Développement durable, de l'Environnement et de la lutte contre les changements climatiques, 2018).

In agricultural settings, groundwater pumping is often seasonal and may intensify during dry periods, whereas municipal well fields typically induce more sustained and spatially coherent drawdown patterns. Industrial groundwater use, associated with manufacturing, resource processing, or energy-related activities, is generally site-specific and may involve continuous or high-capacity withdrawals depending on operational requirements.

The cumulative effect of groundwater withdrawals may have implications that extend beyond water resource management alone. Existing structures and civil infrastructure, which were often designed without explicit consideration of groundwater-induced deformation mechanisms, may therefore be exposed to gradual and spatially variable settlements. These considerations highlight the importance of evaluating groundwater use not only from a water-supply perspective, but also in relation to geotechnical conditions and infrastructure resilience.

3 CLIMATE CHANGE AND WATER BALANCE IN QUÉBEC

3.1 Climatic trends and projections

For the province of Quebec, climate change is synonymous with increased rainfall, as has been the case since the 1950s. For the 2021-2050 horizon, Ouranos (2026) predicts an increase in total annual precipitation of between 45 and 90 mm in the south of Quebec (depending on the climate scenario), compared to current total annual precipitation values ranging from 1053 mm south of Montreal to 1544 mm north of Quebec.

Despite an overall increase in total annual precipitation, severe dry conditions are also to be expected (Ouranos, Sécheresse et changements climatiques: des projections qui varient selon les processus considérés, 2025). Due to climate change, an increase in temperature and evapotranspiration will continue to modify the frequency and intensity of droughts. In southern Quebec, summer and fall river low flows will decrease by 15 to 25 % by 2050 (Ouranos, 2024b). The opposite stays true for winter and spring low flows: increased temperatures and snowmelt, as well as increased precipitation falling as rain in the cold season will cause river low flows to a further increase by 20 % to 50 % in southern Quebec (Ouranos, 2024b).

3.2 Implications for Québec

If conditions are favorable for their recharge, predicted increases in precipitation could have a protective effect on overexploited aquifers. However, in summer and fall, the increase in drought periods could reduce the aquifer’s recharge capabilities, as it is harder for rainfall to penetrate dried-up soils. Furthermore, the predicted increase of low flows in winter and spring does not necessarily mean that aquifers will be recharged, since soils can be frozen during these periods, leading to more runoff and less infiltration.

4 HYDROGEOLOGICAL SETTING

4.1 Geological and hydrostratigraphy

Southern Québec is characterized by a complex hydrostratigraphic framework resulting from the superposition of Paleozoic sedimentary bedrock, Quaternary glacial deposits, and post-glacial marine sediments. In the St. Lawrence Lowlands, fractured carbonate and clastic bedrock formations are commonly overlain by thick sequences of glacial tills, glaciofluvial sands and gravels, and fine-grained marine clays deposited during the Champlain Sea transgression.

From a hydrostratigraphic perspective, these deposits form a multilayered system composed of discontinuous granular aquifers and laterally extensive low-permeability units. Coarse-grained sand and gravel bodies generally constitute productive aquifers, whereas clay- and silt-dominated units act as aquitards, controlling vertical groundwater exchanges and storage. The thickness, continuity, and hydraulic properties of these units vary significantly over short distances, resulting in strong spatial heterogeneity in groundwater flow conditions (Chapuis, 2012).

4.2 Aquifers and aquitards

Both unconfined and confined aquifers are present in southern Québec. Unconfined aquifers are typically associated with surficial glaciofluvial and alluvial deposits and respond rapidly to climatic variability and seasonal recharge. In contrast, confined or semi-confined aquifers occur where permeable bedrock or granular units are overlain by thick, continuous clay and silt sequences.

These fine-grained deposits, particularly marine clays of the Champlain Sea, exhibit low hydraulic conductivity and high compressibility. As a result, they limit vertical recharge while being highly sensitive to changes in effective stress. Long-term groundwater level declines within underlying aquifers may therefore induce consolidation of these aquitards, making them a key component in the assessment of settlement and subsidence potential.

4.3 Infrastructure expansion and population Growth as Drivers of Groundwater Stress

Climate change, combined with sustained population growth and expanding infrastructure networks, is expected to exert increasing pressure on groundwater resources in southern Québec, particularly within the St. Lawrence Lowlands. While climate projections suggest a moderate increase in total annual precipitation, groundwater recharge is anticipated to become more episodic and seasonally constrained. Reduced infiltration during more frequent summer and fall droughts, coupled with limited winter recharge due to frozen or partially frozen ground conditions, is likely to decrease effective recharge to aquifer systems.

These constraints are especially critical in confined aquifer systems common across southern Québec, where natural recharge rates are inherently limited. Under such conditions, prolonged groundwater pumping associated with municipal supply, industrial activities, and major infrastructure development may induce sustained piezometric drawdown. Beyond concerns related to long-term water availability, this drawdown can alter the effective stress regime within overlying compressible aquitards, notably the Champlain Sea clay deposits.

As a result, groundwater exploitation must be assessed not only from a hydrogeological sustainability perspective, but also about its geotechnical implications, including time-dependent consolidation and land subsidence. This integrated hydraulic–mechanical perspective is particularly critical in areas where strategically important infrastructure—such as transportation corridors, ports, and urban developments—overlies clay-rich deposits sensitive to changes in pore-water pressure.

4.4 Implications for groundwater sustainability

The recharge capabilities of aquifers vary, and they will therefore be affected differently by climate change. Unconfined porous aquifers composed of sand and gravel, for example, are considered to have the highest potential for recharge (MELCCFP, 2025).

In contrast, confined aquifers, which are mostly found on the St. Lawrence Platform close to the St. Lawrence River, have limited recharge capabilities due to thick, continuous deposits of fine clay and silt that limit infiltration of rainwater (MELCCFP, 2025).This makes these aquifers more vulnerable to overexploitation and the effects of climate change.

To date, some localized issues regarding water availability have been reported in Quebec, primarily during dry summers and in regions experiencing demographic growth or infrastructure development in the south of the province. As droughts are expected to become more frequent in the future, these issues are likely to become more frequent and severe (MELCCFP, 2025).

Monitoring of the groundwater piezometric level by the RSESQ has revealed both positive and negative trends in groundwater levels for all types of aquifer (captive, semi-captive, and free) in southern Quebec over the past few decades (Governement du Québec, 2026; MELCCFP, 2025). As some of this data is relatively new, there is insufficient data on some wells to confirm any trend in the groundwater level. However, tendencies for these more recently monitored sites should become clear within the next decade.

5 GEOTECHNICAL CONSIDERATIONS

5.1 Compressible soil deposits

Southern Québec, particularly the St. Lawrence Lowlands, is characterized by thick clay–silt deposits associated with the Champlain Sea. These low-permeability soils commonly act as laterally extensive aquitards overlying granular aquifers or fractured bedrock. Due to their high compressibility and low drainage capacity, these deposits are sensitive to long-term changes in groundwater pressure, especially in areas of dense infrastructure (Lefebvre, 1981; Shafaei Shahboulaghi et al., 2025).

5.2 Groundwater Drawdown and Effective Stress Changes

From a geotechnical perspective, groundwater pumping and reduced recharge lower pore-water pressures, thereby increasing effective stress in compressible soils (Lefebvre, 1981). In typical Québec depositional environments—such as Champlain Sea clays and glacial tills—confined and semi-confined aquifer systems develop laterally extensive and persistent drawdown due to low-permeability confining layers. This sustained stress increase induces time-dependent consolidation in fine-grained soils, with settlement magnitude and rate governed by pore-pressure dissipation. Owing to their low permeability and high compressibility, clayey aquitards may continue to deform through secondary compression (Leroueil et al., 1983) even under steady pumping conditions, highlighting the need for long-term monitoring and coupled hydro-mechanical analyses to assess infrastructure impacts.

5.3 Soil Settlement and Subsidence Mechanisms

Groundwater-induced stress changes translate into time-dependent deformation of compressible soil profiles (Tavenas et al., 1978). In fine-grained deposits, settlement develops progressively as pore-water pressures dissipate, often extending beyond the active drawdown phase. At the local scale, this behavior typically results in differential settlement, while sustained and laterally extensive stress changes within thick clay sequences may lead to broader subsidence (Shafaei Shahboulaghi et al., 2025). The magnitude and spatial distribution of deformation are controlled by stratigraphic contrasts between aquifers and aquitards, which govern stress transfer and drainage conditions. As a result, settlement patterns may vary significantly over short distances, particularly in heterogeneous hydrostratigraphic settings.

5.4 Implications for existing structures and infrastructure

Progressive and spatially variable settlements pose a significant risk to existing infrastructure, much of which was designed under assumptions of stable groundwater conditions. Linear assets such as roads, pipelines, and railways are especially sensitive to differential deformation, while shallow-founded structures may experience serviceability issues under relatively modest but uneven settlements (Leroueil, 2001).

In southern Québec, areas where compressible marine clays coincide with confined aquifer systems, intensive groundwater use, and high infrastructure density are particularly exposed. In these settings, gradual deformation processes may remain undetected until functional or structural impacts become evident, underscoring the importance of integrating groundwater trends and geotechnical response into infrastructure risk screening and management. Figure 2 summarizes the geotechnical response of structures and infrastructure to groundwater drawdown and water-level rise, illustrating the main deformation mechanisms and associated risks for different foundation types and ground conditions.

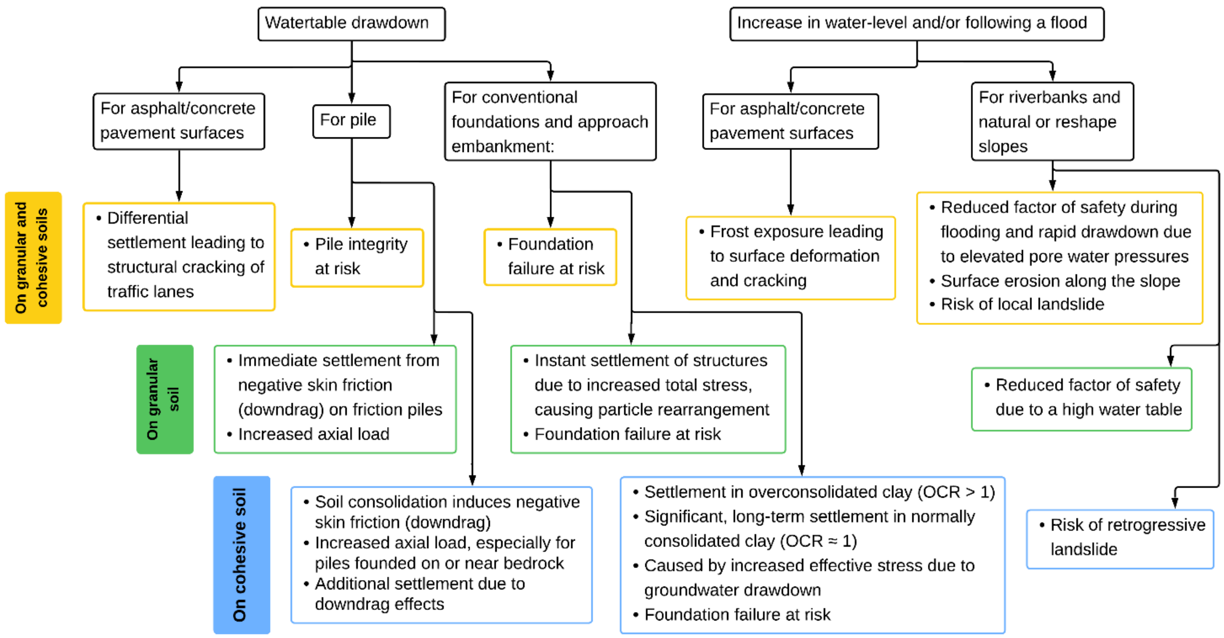

Figure 2. Geotechnical mechanisms and infrastructure risks associated with groundwater level variations

6 INFRASTRUCTURE RESILIENCE AND MITIGATION STRATEGIES UNDER CLIMATE CHANGE

6.1 Climate-related hazards affecting infrastructure

Climate change is expected to exacerbate several hazards that directly affect infrastructure performance in Québec, including prolonged droughts, intense precipitation events, and increased variability in groundwater levels. Drought periods may intensify groundwater abstraction, leading to sustained drawdown, while extreme rainfall and flooding can cause rapid groundwater level recovery or transient pore-pressure increases.

These alternating hydraulic conditions may induce cyclic loading in soils, accelerate degradation processes, and increase the likelihood of differential settlements. Infrastructure founded on compressible soils is particularly vulnerable to these evolving stress regimes, especially when design assumptions did not explicitly account for long-term groundwater fluctuations.

6.2 Hydrogeological and geotechnical risks

Hydrogeological and geotechnical risks are closely interconnected in clay-dominated environments (Leroueil, 2001). Groundwater drawdown reduces pore-water pressure, increases effective stress, and can trigger consolidation of compressible layers, leading to progressive settlement and, in some cases, regional subsidence. Conversely, rapid groundwater rebound—such as after intense rainfall events or flooding—may reduce effective stress and alter stability conditions, with potential implications for slope stability and foundation performance in sensitive or marginally stable settings (Leroueil, 2001).

These processes often evolve gradually and may remain unnoticed until serviceability issues become apparent (e.g., cracking, loss of grade, misalignment, or distress at interfaces). In southern Québec, the spatial heterogeneity of hydro-stratigraphy and the variable thickness and properties of fine-grained deposits (Germain et al., 2021) can amplify the risk of differential settlement, which is typically more damaging to infrastructure networks than uniform deformation. This is particularly relevant where infrastructure corridors cross alternating granular aquifers and compressible aquitards, creating strong contrasts in pore-pressure response and deformation potential over short distances.

The workflow illustrated in Figure 2 integrates hydrogeological drivers and monitoring data with a conceptual representation of aquifer–aquitard coupling and translates groundwater level variations into effective-stress changes and associated deformation mechanisms. These mechanisms—ranging from consolidation and creep to immediate settlement or stability loss—are then linked to infrastructure performance and foundation response. The resulting framework supports asset-specific screening (e.g., pavements, shallow foundations, piles, and slopes) and informs monitoring, mitigation, and adaptation strategies throughout the project life cycle (data acquisition → interpretation → simulation → implementation → performance review).

6.3 Infrastructure vulnerability and exposure

Infrastructure vulnerability results from the combined effects of foundation type, soil stratigraphy, groundwater regime, and duration of exposure to hydro-mechanical changes.

In southern Québec, a large proportion of existing structures and infrastructure networks were designed and constructed several decades ago, under assumptions of relatively stable climatic conditions and groundwater regimes. These assets were generally not conceived to accommodate long-term shifts in recharge patterns, sustained groundwater drawdown, or more frequent hydroclimatic extremes projected under future climate scenarios. As a result, aging infrastructure may exhibit reduced tolerance to gradual, cumulative deformation processes that were not explicitly considered in original design criteria.

High infrastructure density in southern Québec often coincides with areas underlain by marine clays and confined aquifer systems, particularly within the St. Lawrence Lowlands. This spatial overlap increases exposure and exacerbates vulnerability, especially for critical lifelines and legacy assets approaching or exceeding their initial design life. Integrating subsurface conditions, groundwater trends, and asset age into infrastructure resilience assessments is therefore essential to anticipate emerging risks and to guide proactive adaptation, monitoring, and rehabilitation strategies.

6.4 Proposed Mitigation and adaptation strategies

Improving infrastructure resilience under climate change requires a proactive, risk-based, and integrated engineering approach that explicitly addresses the coupling between groundwater dynamics, soil behaviour, and structural performance. Mitigation and adaptation strategies should therefore be implemented across multiple project scales, from subsurface characterization to long-term asset management.

At the system level, enhanced groundwater monitoring is a foundation stone of risk mitigation. This includes the expansion of piezometric networks within both aquifers and compressible aquitards, as well as the use of continuous monitoring technologies to detect gradual drawdown or rebound trends. Adaptive pumping management—such as adjusting extraction rates seasonally, redistributing pumping among wells, or defining drawdown thresholds—can help limit long-term changes in effective stress. Incorporating climate-driven recharge scenarios into groundwater models allows project teams to evaluate future stress conditions rather than relying solely on historical records.

From an engineering perspective, foundation and structural solutions should be selected to accommodate time-dependent and spatially variable ground movements. For new infrastructure or major rehabilitation projects, this may include:

- foundation systems with higher tolerance to differential settlement (e.g., piles extending to competent strata, compensated foundations, or raft foundations where appropriate);
- structural detailing that allows controlled deformation, such as flexible joints, articulation zones, and modular elements along linear infrastructure;
- staged construction or preloading strategies designed to accelerate consolidation and reduce post-construction settlement uncertainty.

Ground improvement techniques—such as vertical drains, preloading, deep soil mixing, or selective replacement—may be applied in localized high-risk zones to reduce compressibility or shorten consolidation time. The selection of these measures should be supported by hydro-mechanical analyses that explicitly account for groundwater-induced stress changes rather than surface loading alone.

At the planning level, land-use decisions and infrastructure siting should incorporate long-term groundwater behaviour and soil compressibility, particularly in regions underlain by marine clays and confined aquifers. For existing and aging infrastructure, adaptation strategies should emphasize risk screening and prioritization, combining asset criticality, design life, observed performance, and subsurface vulnerability. Integrating groundwater and geotechnical indicators into asset management frameworks enables early identification of corridors or assets requiring targeted monitoring, retrofit, or operational adjustment.

Ultimately, effective adaptation relies on the integration of hydrogeology, geotechnics, structural engineering, and climate science within a unified decision-support framework. By linking monitoring data, conceptual and numerical models, and engineering performance criteria, infrastructure owners and designers can move from reactive maintenance to anticipatory resilience planning. This integrated approach is essential to ensure the long-term safety, functionality, and sustainability of infrastructure systems under evolving climatic and hydrogeological conditions.

7 CONCLUSIONS

This paper highlights the growing interconnection between climate change, groundwater management, and geotechnical performance in Québec. While groundwater has long been regarded as a resilient and reliable resource, increasing climatic variability combined with sustained abstraction raises significant concerns regarding long-term settlement and land subsidence in clay-rich environments. The St. Lawrence Lowlands, where high population density and infrastructure concentration coincide with geotechnically sensitive deposits, appear particularly exposed to these evolving risks.

Addressing these challenges requires an integrated water–soil–infrastructure perspective to adequately assess vulnerability and support informed, long-term decision-making. Future research should prioritize the coupling of groundwater monitoring data with geotechnical observations and the development of predictive tools that explicitly account for climate-driven groundwater fluctuations.

8 AKNOWLEDGEMENT

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practitioners in Québec, is essential to advancing knowledge and improving infrastructure resilience under changing climatic conditions.

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