RESEARCH NOTE

How Hydrology Shapes the Design — and Cost — of High-Speed Rail

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CORE FINDING

Hydrology is one of the most consequential and least publicly discussed constraints on high-speed rail design. The fundamental problem is precision: HSR slab track must maintain alignment to within **15 mm of post-construction settlement** — two-thirds of an inch — over its entire operational lifetime. Water is the primary agent of settlement. Every HSR design decision ultimately flows from the need to keep water away from the subgrade, or to ensure that when water is present, it drains fast enough and uniformly enough that it cannot create differential settlement across the track. This has direct and significant implications for the ALTO route choice in Eastern Ontario.

1. The Tolerance Problem: Why HSR and Water Don't Mix

The fundamental reason hydrology matters so much more for high-speed rail than for conventional rail is the extraordinary precision required of the track structure. High-speed trains operating at 300 km/h impose dynamic forces on the track that are orders of magnitude greater than those of slower trains, and those forces amplify any geometric irregularity. A millimetre of misalignment that would be imperceptible at 100 km/h can cause dangerous oscillations at 300 km/h.

For ballastless (slab) track — the standard for modern high-speed rail — **post-construction settlement of the subgrade must be kept below 15 mm**. That is approximately two-thirds of an inch, over the entire operational lifetime of the line. This is not a construction quality standard; it is a permanent operational requirement. Large subgrade differential settlement induces additional stress in the monolithic track bed and significantly affects track geometry irregularity — and crucially, that irregularity **cannot be fully recovered by routine maintenance** on a ballastless track in the way that ballasted track can be tamped back into alignment.

Water is the primary agent that causes settlement. Saturated or repeatedly wetted soils consolidate under load, lose bearing capacity, and shift in ways that dry, stable ground does not. The seasonal freeze-thaw cycle of a Canadian climate adds further complexity: water that infiltrates a subgrade and then freezes can cause frost heave — upward displacement — followed by settlement on thawing. Even small gradients of differential movement across the track structure translate directly into safety and comfort problems at operating speed.

2. Mud Pumping: The Specific Failure Mode of Wet Slab Track

Mud pumping is a specific and serious failure mode that affects high-speed slab track under wet conditions, and it has no real equivalent in conventional railway engineering. Understanding it is essential to understanding why drainage design is so critical — and so expensive.

2.1 How It Happens

Extreme rainfall events — and even moderate persistent rainfall without adequate drainage — can cause water to infiltrate the narrow gaps between the concrete base slab and the underlying roadbed surface. Under the repeated dynamic loading of passing trains at high frequency and speed, fine soil particles are literally pumped upward through those gaps. The result is progressive voiding beneath the slab: the slab is supported in some places and unsupported in others, creating exactly the differential settlement the track cannot tolerate. Research has confirmed that **mud pumping occurs only when structural gaps, ponding, and cyclic loading coincide** — which means it is both predictable and preventable, but only if drainage is designed correctly from the outset.

2.2 Rainfall and Risk

Research using structural equation modelling on China's extensive high-speed rail network has shown that both train operating frequency and rainfall significantly affect mud pumping occurrence. Counterintuitively, **moderate but persistent rainfall is actually more dangerous than extreme storms**. Areas that experience extreme rainfall events are typically designed with better drainage infrastructure specifically because of the obvious risk. It is the chronic moderate rainfall — particularly combined with imperfect drainage — that causes progressive failure over time. In a climate like Eastern Ontario's, with relatively consistent annual precipitation spread across many months and a significant freeze-thaw cycle, this is a material long-term operational consideration.

2.3 Prevention and Its Costs

The engineering response to mud pumping risk is a multi-layered drainage system. The roadbed surface beneath the concrete base must be effectively sealed with asphalt concrete to prevent vertical infiltration. Rainwater that enters the shoulder area must be rapidly evacuated through permeable shoulder fill and blind ditches designed to specific hydraulic conductivity standards. Research has shown that an optimized drainage retrofit using permeable shoulders and blind ditches — with hydraulic conductivity above 23 mm/s — **reduces ponding time by up to 90%** under one-year recurrence storms. This is achievable, but the engineering requirements are demanding and site-specific, requiring regional rainfall calibration.

DESIGN CONSEQUENCE

The mud pumping problem means that high-speed rail drainage design cannot be treated as a secondary consideration during route planning. Sites with high water tables, seasonally wet soils, or frequent stream crossings require substantially more complex and expensive drainage engineering. This cost is not just in construction — it persists through the operational lifetime of the line as monitoring, inspection, and potential grouting or remediation work.

3. The Subgrade Hierarchy: Water, Soil, and Settlement

Geology and hydrology are inseparable in HSR design. The type of soil or rock beneath the track determines how water behaves, how settlement occurs, and what engineering interventions are required. HSR projects must assess and address three distinct water-related subgrade challenges.

3.1 Groundwater Table

A high water table creates upward pressure against the subgrade and reduces bearing capacity by saturating soils. In frost-susceptible soils, it also creates seasonal freeze-thaw cycling risk. Research on China's HSR network has found that **climatic factors — particularly the interaction between annual rainfall and freezing days — predominantly influence frost damage in HSR subgrades**, underscoring that this is a Canadian climate concern as much as it is a global one. Areas with seasonally high water tables require either deep drainage installation to lower the table below the depth of frost penetration, or the use of frost-resistant fill materials — both of which add significant cost.

3.2 Soft Soils and Long-Term Settlement

Soft soils — clays, silts, peats — have high compressibility and low permeability. Under the sustained load of an embankment and the dynamic load of passing trains, they consolidate slowly over years and decades. This is the dominant challenge in low-lying areas with lacustrine (lake-deposited) or marine clays. **Due to the high compressibility and low permeability of soft soil, post-construction settlement is extremely difficult to control** — seriously threatening the operation safety of high-speed trains. Standard treatment options include pre-loading (applying a temporary surcharge load before track construction to accelerate consolidation), installation of vertical drain systems (plastic drainage plates or stone columns to accelerate drainage), or pile foundations carrying the track structure directly to stable bearing strata below the soft layer. All are expensive, and all require extensive geotechnical investigation to design correctly.

3.3 Expansive Clays

Clays that swell when wetted and shrink when dried create cyclical heave and settlement that is particularly damaging to slab track. **High-speed railways operating above 200 km/h have very small differential settlement tolerance, making it extremely difficult to meet rigorous settlement limitations in zones of expansive soil**. The Kunming-Shanghai HSR in China encountered this problem extensively, requiring the development of novel waterproof functional layers specifically to manage the problem. Southern Ontario's clay-till soils do not generally exhibit the extreme expansivity seen in some Chinese geological settings, but any section of the southern ALTO corridor passing through clay-rich terrain will require careful assessment.

4. Floodplains, Wetlands, and Watercourse Crossings

Every time a high-speed rail line crosses a watercourse, floodplain, or wetland, it triggers a cascade of engineering requirements and regulatory obligations. These are not incidental — they are among the most technically complex and cost-intensive elements of HSR design.

4.1 The Engineering Requirements

HSR crossings of floodplains and rivers must be designed to maintain the hydraulic function of the watercourse — the railway cannot simply act as a dam that backs water up on the upstream side. Regulatory requirements in Canada require that proposed structures not increase base flood elevations, and that bridge structures provide **flow conveyance and connectivity**. In practice this means bridges designed to pass the 100-year flood event without overtopping, with sufficient span and clearance to accommodate flood flows plus debris and ice.

The design process for each watercourse crossing requires: a full hydrological assessment of the watershed and flood frequency; a hydraulic model of the stream cross-section, floodplain, and proposed structure; scour analysis (assessment of how much bed material will be eroded around bridge foundations at high flow); and regulatory review by Conservation Authorities, Transport Canada, and Fisheries and Oceans Canada (under the Fisheries Act) for any work affecting fish habitat.

Unlike a road crossing — where a culvert is often adequate — HSR cannot use culverts for any significant watercourse, because culverts create the grade change and local ponding that would destabilize the subgrade. Bridges are required. Each bridge must be founded on piles or piers that penetrate below the scour depth — the depth to which the riverbed is eroded during a major flood — which requires deep foundation investigation at every crossing site.

4.2 The Piled Viaduct Solution for Wetlands

Where ground conditions are so poor that conventional subgrade preparation cannot achieve the required settlement tolerances, the solution is to take the track off the ground entirely on a piled viaduct structure. This approach was used on High Speed 1 in the United Kingdom, where **piled slab track — essentially a viaduct in the ground — was used to traverse the highly unstable East Thames marshes**. This is technically reliable but enormously expensive. It converts what would otherwise be an earthworks problem (grading, compaction, drainage) into a structural problem (pile design, concrete formwork, structural inspection over the operational lifetime of the line).

For sections crossing significant wetland complexes — which are common in the Frontenac Arch region and in the transitional terrain between the Shield and the Palaeozoic cover— a piled viaduct approach may not be avoidable. The alternative, building a conventional embankment through a wetland by excavating the weak material and replacing it with granular fill, extensively disturbs local hydrology, affects adjacent land drainage, and triggers significant permitting requirements under Ontario's Conservation Authorities Act and Wetlands policies.

4.3 Secondary Hydrological Impacts

A high-speed rail track, consisting of linear embankments and cuttings running across the landscape, acts as a dam or drainage divide. On the upslope side, it intercepts natural drainage and must redirect it through engineered structures (culverts, ditches, or bridges). On the downslope side, drainage patterns are altered. In areas with clay-till soils, these secondary hydrological effects can affect adjacent farmland drainage for hundreds of metres from the corridor. In Ontario, **the hydraulic conductivity of clay tills depends heavily on the degree of fracturing, and subsurface hydraulic connectivity between wetlands is common** — meaning that an embankment disrupting groundwater flow in one location can affect wetlands at a distance that was not initially apparent.

5. The Slab Track Commitment and Its Hydrological Implications

Modern high-speed rail is almost universally built with ballastless slab track rather than traditional ballasted track. The choice is driven partly by water.

5.1 Why Ballast Fails at High Speed

At speeds approaching 300 km/h, the aerodynamic forces generated by passing trains are sufficient to lift ballast particles from the track bed and project them at high velocity — the "ballast pick-up" or "ballast flight" problem. These particles damage rolling stock and can be dangerous. At these speeds, **fine particles can be sucked out of the track by the passing train and deposited on the rail surface, causing damage when run over by the wheels**. In some applications this has required glued ballast to stabilize the track bed. Ballasted track also requires frequent tamping maintenance to correct geometry — a process that is expensive and time-consuming, and that becomes increasingly difficult to schedule as train frequencies increase on the line.

5.2 Slab Track Advantages — and Its Critical Vulnerability

Ballastless slab track addresses these problems. It offers **highly consistent track geometry, a longer service life of up to 100 years, reduced maintenance needs, better controlled drainage, and elimination of the ballast pick-up problem**. Construction tolerances for slab track installation are extremely tight — the concrete must be poured to ±1.0 mm precision. The slab provides a stable, monolithic platform that does not require tamping.

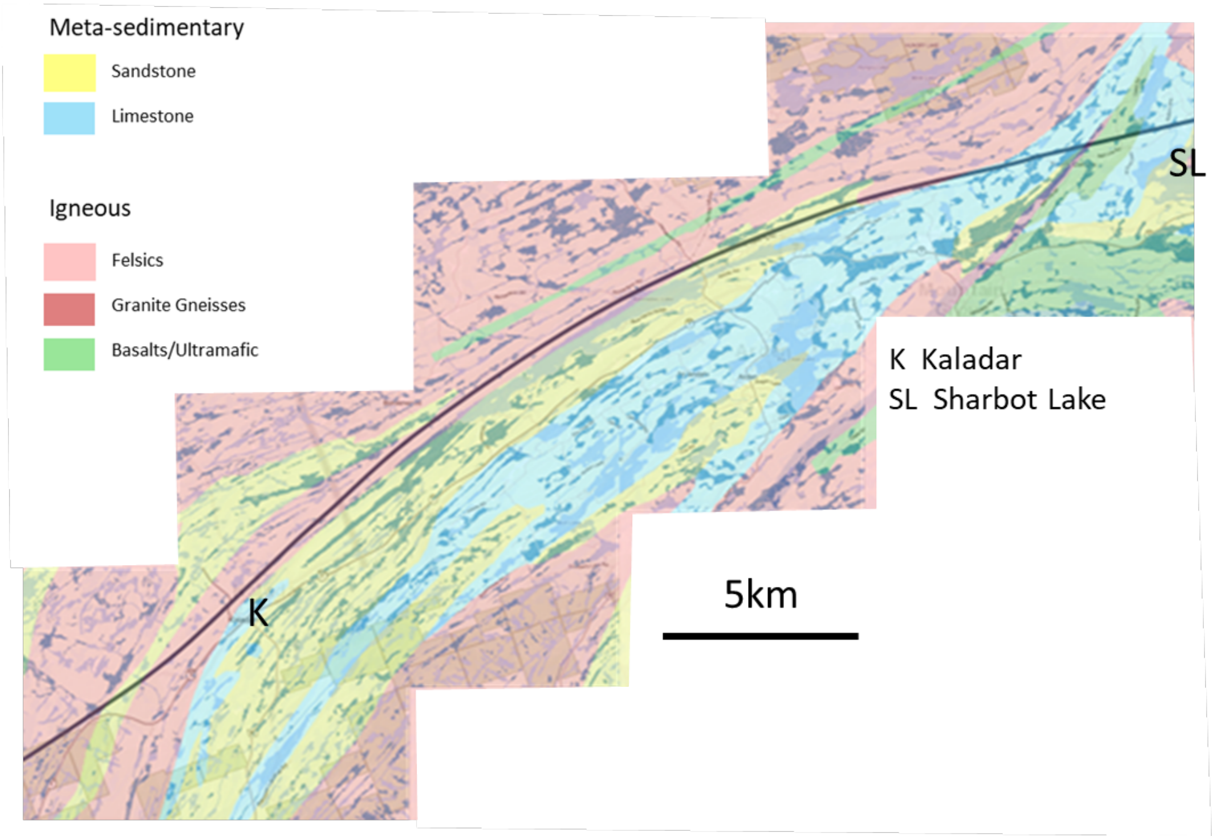
The critical vulnerability is the obverse of this strength: if slab settlement does occur — if the subgrade beneath the concrete shifts — **there are no simple solutions**. Unlike ballasted track, where settlement is corrected by adding ballast and tamping, slab track settlement requires grouting beneath the slab, underpinning, or in serious cases complete removal and reconstruction of affected sections. This is expensive, disruptive, and cannot be performed quickly during a normal maintenance window. The slab track commitment therefore means that getting the subgrade right at the outset is not merely desirable — it is functionally mandatory. And getting the subgrade right means getting the drainage right.

6. What This Means for ALTO Route Choices in Eastern Ontario

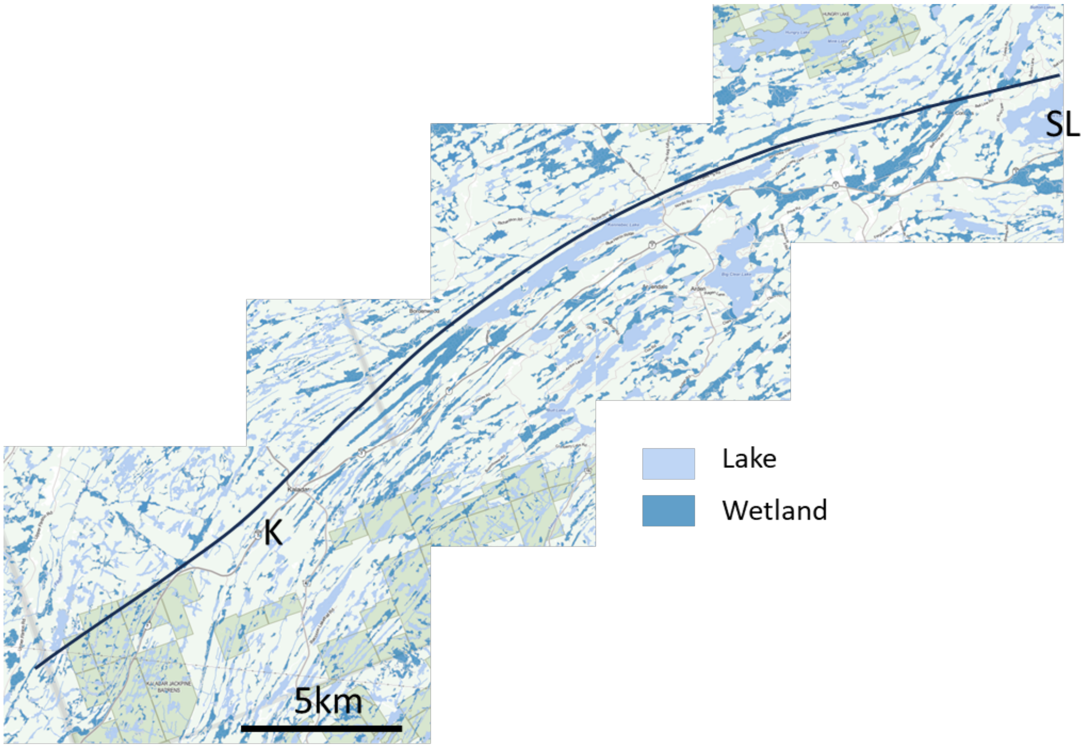
The ALTO northern vs. southern corridor comparison is, at its core, a trade-off between two fundamentally different hydrological problem sets. The public framing has emphasised rock (northern) vs. agricultural land (southern). The hydrological reality is more nuanced — and consequential.

6.1 Wetlands analysis.

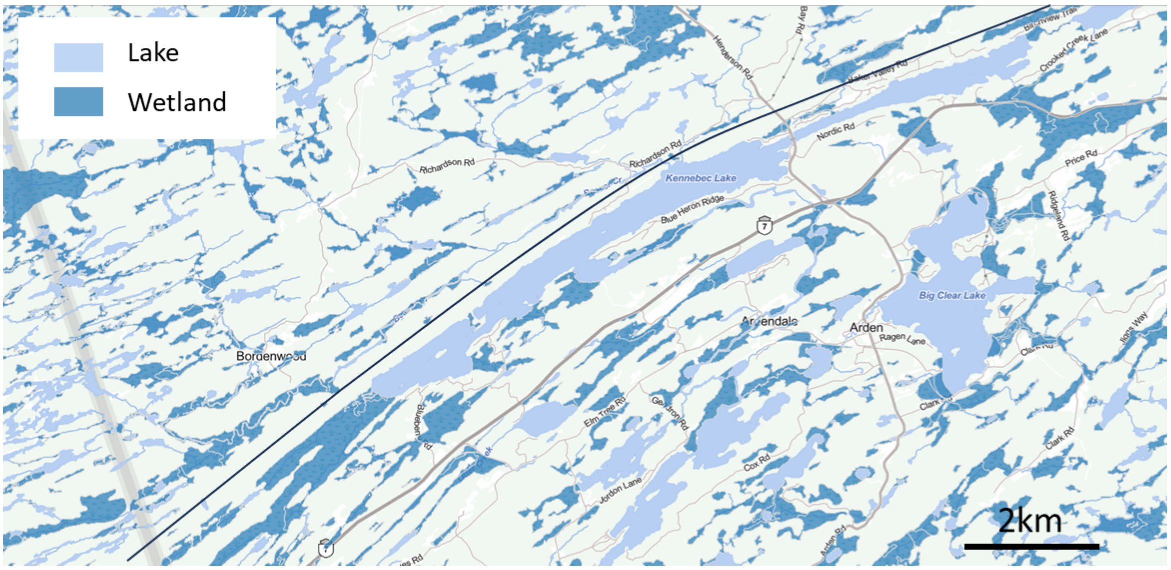
A perception exist that the northern route on shield is poorly drained with many wetland features that need to negotiated. However, just as the geology controls the geomorphology so it controls the distribution and geometry of the wetlands. Within the Mazinaw geological terrane the wetlands, like the lakes, tend to be elongate in the direction of geological strike which fortuitously is parallel with the railway alignment.



Geological control results in a very pronounced shape anisotropy in the distribution of wetlands with the majority being elongate in te direction of railway alignment

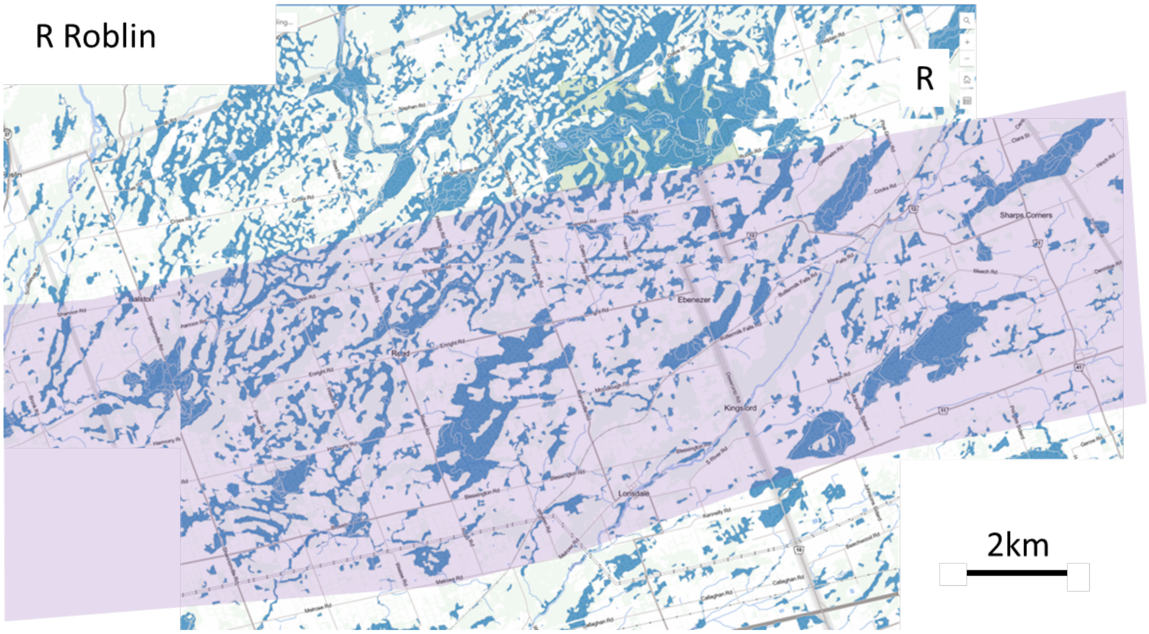


A 50km long alignment can be routed through the Mazinaw terrane without crossing a major lake or wetland. Source: Ontario geohub: https://geohub.lio.gov.on.ca/



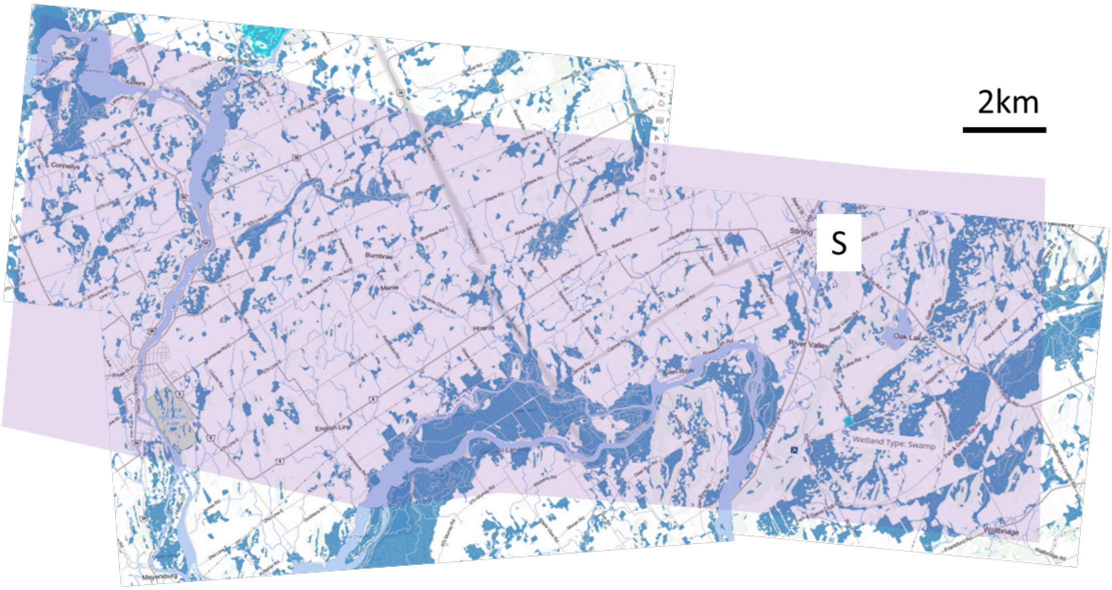
Detailed map of wetlands in Mazinaw terrane. Ontario geohub: https://geohub.lio.gov.on.ca/

At first glance the southern corridor may seem more attractive since there are less wetlands owing to the agricultural drain that has been conducted over the last 200 years. However, in actual fact the wetland areas are more abundant and considerably more disorganised in distribution and form.



The Southern Corridor North of Napanee and south of Roblin.

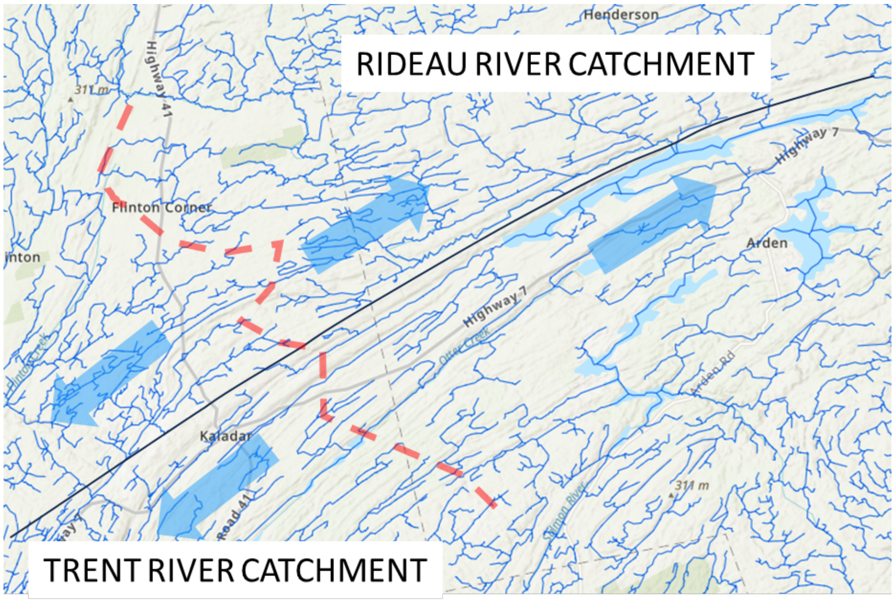
Ontario geohub: https://geohub.lio.gov.on.ca/



The Southern Corridor North of Belleville, with Stirling indicated on the map. Wetlands around the Trent River dictate a more northern alignment. S: Stirling (pop: 2071:2021). Ontario geohub: https://geohub.lio.gov.on.ca/

The wetlands themselves comprise the most delicate and diverse ecological corridors through the landscape. The drain into and are inter-connected with rivers and watercourses. From a watershed perspective the two routes are very different.

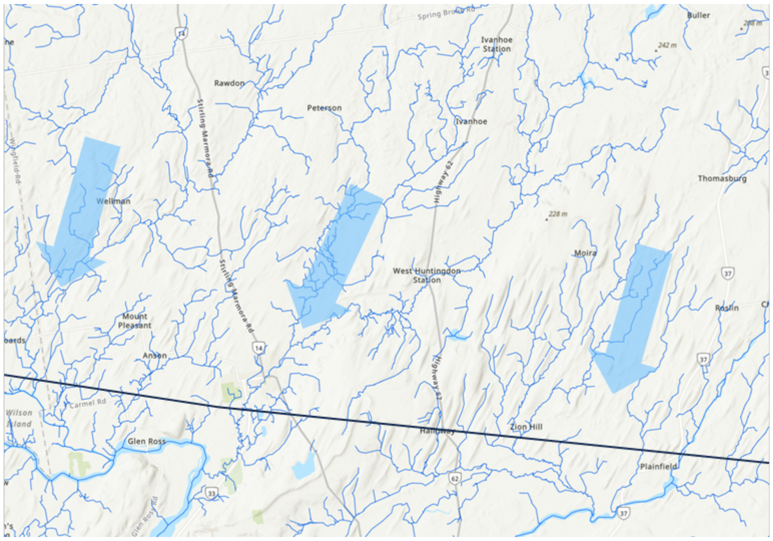
The northern route occupies a “headwater” location near the upper reaches of the Trent river and Rideau River watersheds. Geomorphologically this consists of small elongate wetlands interconnected with streams running NE-SW (Trent catchment) and SW-NE (Rideau catchment).



Watercourses for the Northern route. The predominately SW-NE flow patterns are parallel with the railway alignment and result from the interplay of geology, geomorphology and hydrology.

The southern corridor represents a downstream watershed setting as the contents of the Cataraqui, Napanee, Salmon, Moira and Trent rivers drain south into Lake Ontario. These watercourses can experience prolonged spring runoff periods as the snowpack melt extends north. Ice-damming with associated flooding is a common occurrence.

On first impression the southern route appears to contain fewer water courses. However, the agricultural land has been drained by an intricate system of tile drainage that directs water off increasingly large fields into the moderate sized streams and rivers. The discharge can be quite rapid since the capability of the landscape to act as a sponge has been disrupted.



Napanee: 820km^2

Salmon: 921km^2

Moira: 3,000km^2

Trent: 12,000 km^2

Ave annual rainfall (approx. 1000mm)

Potentially 10,000 trillion litres of water must cross southern alignment.

The water flow on the southern route is perpendicular to the proposed alignment meaning that as much as 10,000trillion littles of water will need to flow across the alignment.

Challenge	Northern Route (Highway 7 / Canadian Shield)	Southern Route (Frontenac Arch / Agricultural Lowlands)
Subgrade stability	Granite bedrock: essentially permanent, zero post-construction settlement risk, no mud pumping, no frost heave in rock sections	Clay-till soils (Champlain) with seasonal elevated water tables: ongoing consolidation risk, frost heave exposure, expansive clay potential in some sections
Watercourse crossings	Watershed headwater setting. Small water sources (1-10km^2 catchment) run parallel to the alignment. Many may be seasonal.	More numerous crossings of smaller streams, drainage channels, and tile-drain systems; each requires hydraulic assessment and bridge structure
Wetland interaction	Blast rubble from rock cuts can be used to fill adjacent wetlands, reducing quarrying needs; engineering and environmental issue but manageable.	Extensive wetland complexes in transitional terrain; corridor may require piled viaduct sections; secondary drainage impacts on adjacent farmland
Drainage engineering	Simpler: cut sections in rock drain naturally; embankment sections on stable, well-drained granular material	Complex: sealed subgrade layers, permeable shoulders, blind ditches, extensive interceptor ditch systems required throughout
Construction cost driver	Acute: blasting, rock removal, cut-and-fill are expensive but front-loaded and finite	Chronic: more stream crossings, more drainage infrastructure, potential soft-ground treatment; costs distributed and ongoing
Long-term operational risk	Low: rock foundation does not change; drainage system simple to maintain	Moderate to high: clay consolidation continues for years; drainage systems require ongoing inspection; any failure requires expensive slab track repair

6.1 Northern Corridor: Unexpectedly Manageable and Finite

The northern corridor's primary challenge is rock: blasting through or adjacent to the metasedimentary corridor, managing large volumes of excavated material, achieving the gentle horizontal and vertical curves that 300 km/h operation demands across irregular terrain. Due to the geological structure of the Mazinaw Terrane, by following the structural strike direction, cut and fill is minimized over the western 50km of the Canadian shield transect. But from a hydrological standpoint, granite is about as favourable a foundation as exists. It doesn't settle. It doesn't pump mud. It doesn't swell with moisture or consolidate under load. Drainage in cut sections is entirely passive — water drains away from the track naturally. Drainage is facilitated because the small streams drain along the structural strike which is parallel with the railway alignment. Hence the railway does not provide a dam to the pre-existing natural drainage pattern. The headwater setting makes the railway less susceptible to intense rain events compared to the down-stream southern route.

Where the northern corridor crosses wetlands adjacent to rock cuts — and it will, because rock outcrops and wetland basins are common companions on the Shield — blast rubble from the rock excavation is a ready-made fill material. However once again these wetlands tend to be elongate along the geological strike, and by good fortune can be conveniently navigated around for 10-20km lengths. Further east in the Sharbot Lake terrane, the geology is more complex but still reflects the SW-NE geological structure and so the lakes and wetlands still have elongate shapes parallel to the railway alignment. Most important the predominant drainage direction is still almost parallel to the railway. The local availability of high-quality fill that can be obtained as the route crosses the Sharbot lake obstacle will be into a partial engineering solution.

The northern corridor's hydrological challenges are unexpectedly manageable and predictable due to their headwater location. They occur at specific crossing points and the relatively low-volume headwater catchment’s that can be identified through desktop assessment before construction, designed to a known standard, built, and then left largely undisturbed for decades. The bed-rock foundation does not change.

6.2 Southern Corridor: Distributed and Chronic

The southern corridor, by contrast, presents hydrological challenges that are distributed, time-dependent and ongoing. The route transects the Frontenac Arch before transitioning from thin-soiled granite to clay-till agricultural lowlands, with numerous streams, seasonal wetlands, tile-drained farmland, and floodplains along the way.

ALTO's own corridor description acknowledges that the southern corridor crosses sensitive wetlands, and local opponents have specifically noted this. The Cataraqui Trail — one of the existing linear features ALTO is examining — **crosses sensitive wetlands**. The engineering consequence of this is not merely aesthetic or environmental: it is that every wetland intersection requires a technical solution, a permit, and a long-term monitoring obligation. Further west the Napanee, Salmon, Moira and potentially Trent Rivers must be negotiated. Closer to Peterborough the predominant drainage pattern, running parallel to the drumlin morphology, runs perpendicular to the proposed alignment which effectively turns the railway embankments into dams or impoundments.

Clay-till soils in southern Ontario do not provide the stable, predictable foundation that rock does. Their hydraulic conductivity — how quickly they transmit water — varies with depth, fracturing, and seasonal groundwater levels. Subsurface hydrological connectivity between wetlands in these soils means that an embankment disrupting groundwater flow in one location can affect drainage over a larger area than is initially apparent. The tile drainage systems that underlie current and historical agricultural land in this corridor would be intersected by the railway and would require detailed assessment and in many cases reconstruction.

KEY DISTINCTION

The northern corridor's hydrological challenges are **predictable and manageable** — especially in the Mazinaw terrane rocks, but inherently stable once built. The southern corridor's hydrological challenges are **chronic** — embedded in the operational lifetime of the line as an ongoing obligation for monitoring, drainage maintenance, and potential subgrade remediation. For a line intended to operate for 60–100 years, this distinction matters enormously to whole-of-life cost. Chinese HSR experience suggest that 20% of the cost-to-build will be required for maintenance between 20 – 30 years of operational life.

7. Implications for the ALTO Environmental Assessment

The hydrological analysis above has several direct implications for the ongoing ALTO public consultation and the environmental assessment process that must follow.

- **Baseline survey requirement:** A rigorous hydrological baseline study of both corridors is essential before any route recommendation is made. This must include mapping of watercourses, floodplain extents, wetland complexes, tile drainage systems, and groundwater depths along the entire study area. Desktop assessment from aerial photography and existing mapping is insufficient for a project of this magnitude.
- **Crossing inventory:** The number and character of watercourse crossings in each corridor option should be a published input to the route comparison — not a detail left to the environmental assessment phase. Each crossing is a known cost driver and regulatory trigger.
- **Construction cost framing:** ALTO's narrative that a route chosen through the southern corridor 'simplifies construction' relative to one in the northern corridor is inaccurate. Unexpectedly favourable rock -types (Mazinaw Terrane meta-sediments) across a 50km traverse of the Northern shield, compared to the complication in drainage engineering, stream crossings, and soft-ground treatment on the southern route, will significantly favor (>40%) the former in whole-of-life cost terms.
- **Conservation Authority engagement:** Conservation Authorities covering both corridors — Rideau Valley, Cataraqui Region, Quinte, Lower Trent— should be formally engaged in the consultation process. Their regulatory role in floodplain and wetland management will be triggered by any route construction.
- **Whole-of-life costing:** The public consultation should explicitly address the operational maintenance cost implications of each route, not only construction cost. The favourable geology related to the Highway 7 meta-sedimentary (Mazinaw and Sharbot Lake terranes) combined with a much simpler hydrological problem, combined, will result in 25-40% lower cost-to-build. Most importantly, a route through the southern corridor will

require substantially more ongoing drainage maintenance and monitoring making it a significantly more expensive choice) over a 60-year operational horizon.

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