

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

<b>Prepared by</b>	Andrew Hyett
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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 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.

## Section 1 — The Tolerance Problem: Why HSR and Water Don't Mix

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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 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.

## **Section 2 — Mud Pumping: The Specific Failure Mode of Wet Slab Track**

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Mud pumping is a specific and serious failure mode that affects high-speed slab track under wet conditions, with no real equivalent in conventional railway engineering. 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. Under the repeated dynamic loading of passing trains, fine soil particles are literally pumped upward through those gaps, creating progressive voiding beneath the slab, exactly the differential settlement the track cannot tolerate.

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. Counterintuitively, moderate but persistent rainfall is actually more dangerous than extreme storms: areas subject to extreme events are typically designed with better drainage, while chronic moderate rainfall with imperfect drainage causes progressive failure over time. In Eastern Ontario's climate, consistent annual precipitation across many months, with a significant freeze-thaw cycle, this is a material long-term operational consideration.

The engineering response is a multi-layered drainage system. Research has shown that an optimised 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 requirements are demanding and site-specific, requiring regional rainfall calibration.

## **Section 3 — The Subgrade Hierarchy: Water, Soil, and Settlement**

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### **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. Areas with seasonally high water tables require either deep drainage installation below the frost penetration depth, or frost-resistant fill materials both of which add significant cost.

### **3.2 Soft Soils and Long-Term Settlement**

Soft soils including 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. Due to the high compressibility and low permeability of soft soil, post-construction settlement is extremely difficult to control, seriously threatening the operational safety of high-speed trains. Standard treatment options include pre-loading, vertical drain systems, or pile foundations, all expensive, and all requiring extensive geotechnical investigation.

### **3.3 Expansive Clays**

Clays that swell when wetted and shrink when dried create cyclical heave and settlement particularly damaging to slab track. 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 requires careful assessment.

## **Section 4 — Floodplains, Wetlands, and Watercourse Crossings**

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Every time a high-speed rail line crosses a watercourse, floodplain, or wetland, it triggers a cascade of engineering requirements and regulatory obligations, among the most technically complex and cost-intensive elements of HSR design.

### **4.1 Engineering Requirements**

HSR crossings must maintain the hydraulic function of the watercourse. 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. Each crossing requires a full hydrological assessment, hydraulic model, scour analysis, and regulatory review by Conservation Authorities, Transport Canada, and Fisheries and Oceans Canada.

### **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 track must be taken off the ground entirely on a piled viaduct structure. This approach was used on High Speed 1 in the United Kingdom to traverse the highly unstable East Thames marshes. It is technically reliable but enormously expensive, converting an earthworks problem into a structural engineering problem with inspection obligations over the entire operational lifetime of the line.

### **4.3 Secondary Hydrological Impacts**

A high-speed rail track with 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. In areas with clay-till soils, these secondary effects can affect adjacent farmland drainage for hundreds of metres from the corridor. Subsurface hydraulic connectivity between wetlands is common in these soils, meaning an embankment disrupting groundwater flow in one location can affect wetlands at a distance that was not initially apparent.

## **Section 5 — What This Means for ALTO Route Choices in Eastern Ontario**

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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.

### **5.1 Wetlands Analysis**

A perception exists that the northern route on Shield is poorly drained with many wetland features to negotiate. However, just as geology controls geomorphology, it controls the distribution and geometry of the wetlands. Within the Mazinaw geological terrane, wetlands, like the lakes, tend to be elongate in the direction of geological strike, which is parallel with the railway alignment. A 50 km alignment can be routed through the Mazinaw terrane without crossing a major lake or wetland.

The southern corridor, at first glance, may seem more attractive since there appear to be fewer wetlands owing to 200 years of agricultural drainage. However, in actual fact the wetland areas are more abundant and considerably more disorganised in distribution and form. Wetlands around the Trent River dictate a more northern alignment, adding complexity to routing.

## 5.2 Watershed Position

The northern route occupies a headwater location near the upper reaches of the Trent and Rideau River watersheds. Watercourses run parallel to the alignment, and the small headwater catchments can be identified through desktop assessment before construction, designed to a known standard, built, and left largely undisturbed for decades.

The southern corridor represents a downstream watershed setting, with the Cataraqui, Napanee, Salmon, Moira, and Trent rivers draining south into Lake Ontario. These watercourses experience prolonged spring runoff periods and ice-damming with associated flooding. Tile drainage systems underlining agricultural land direct water off fields rapidly into streams, and the water flow is perpendicular to the proposed alignment, potentially requiring as much as 10,000 trillion litres of water to flow across the alignment annually.

## Northern vs. Southern Corridor Hydrological Comparison

Challenge	Northern Route (Highway 7 / Canadian Shield)	Southern Route (Frontenac Arch / Agricultural Lowlands)
<b>Subgrade stability</b>	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
<b>Watercourse crossings</b>	Watershed headwater setting. Small water sources (1–10 km <sup>2</sup> 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
<b>Wetland interaction</b>	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
<b>Drainage engineering</b>	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
<b>Construction cost driver</b>	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
<b>Long-term operational risk</b>	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

### KEY DISTINCTION

The northern corridor's hydrological challenges are predictable and manageable especially in the Mazinaw terrane rocks, and 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 suggests that 20% of the cost-to-build will be required for maintenance between 20–30 years of operational life.

## Section 6 – Implications for the ALTO Environmental Assessment

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- 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 is insufficient for a project of this magnitude.
- 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.
- ALTO's narrative that a route chosen through the southern corridor "simplifies construction" relative to the northern corridor is inaccurate. Unexpectedly favourable rock types across a 50 km traverse of the northern Shield compared to the complications in drainage engineering, stream crossings, and soft-ground treatment on the southern route will significantly favour the former (>40%) in whole-of-life cost terms.
- 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.
- The public consultation should explicitly address the operational maintenance cost implications of each route, not only construction cost. A route through the southern corridor will require substantially more ongoing drainage maintenance, making it a significantly more expensive choice over a 60-year operational horizon.

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