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A Sustainable Solution to Water Scarcity: Modelling the feasibility of a Canada to Great Plains Water Pipeline

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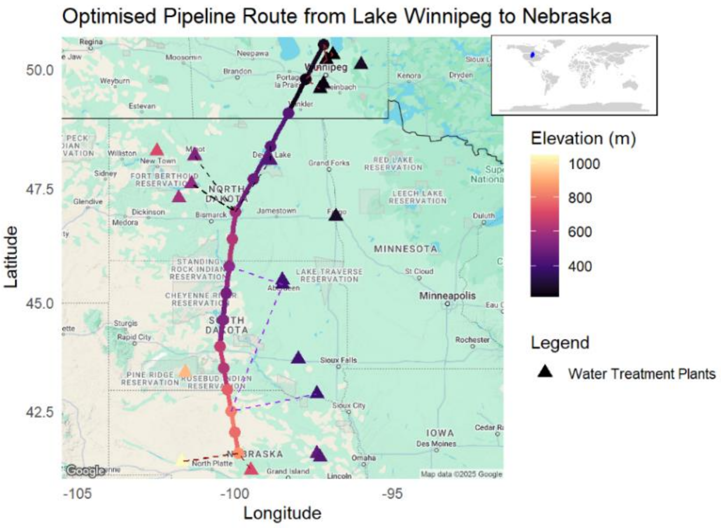
Graphical Abstract



Population Served: *115,461 (Treatment Plant Areas)*

Pipeline Length: *1533.16 km*

Pumping Energy and Consumer Costs: *58,286,864 USD*

Capex: *7 to 10 billion USD*

Opex: *110 to 170 million USD*

Emissions: *94,927,623 kg CO2*

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Abstract

The proposed water pipeline project presents a multifaceted feasibility analysis across economic, engineering, and future considerations. Economically, while the initial capital expenditure (CAPEX) and operational expenditure (OPEX) are significant, they are seen as potentially viable within the $92 billion agricultural market of the Great Plains. A cost-management strategy combining a pay-per-use model, public-private partnerships, and government grants will ensure equitable access. However, looking throughout history, rejections like the North American Water and Power Alliance (NAWAPA), estimated at $760 billion to $1.5 trillion in today's dollars, highlight the political and economic hurdles of a project such as this. From an engineering perspective, the pipeline is deemed technically feasible, with route optimization minimizing elevation changes, energy use, and distance. The annual energy and pumping costs are estimated at $58 million USD, with water services expected to reach 115,000 people across 40,000 properties. To cover these expenses, an average annual water bill of $1,400 USD per property is proposed. This model emphasizes the need to balance cost sustainability while ensuring affordable and equitable water access for various sectors.

Challenges such as biofouling from invasive species like zebra mussels can be mitigated through filtration systems and HDPE materials, while pressure management and soil temperature considerations ensure stability. Nonetheless, reliance on renewable energy from Manitoba Hydro could strain resources due to reduced Nelson River flow, raising concerns about downstream hydropower and grid power demands.

Future directions include the potential scalability of the pipeline to the Southern Great Plains, contingent upon economic and geopolitical approvals. Environmental sustainability requires thorough groundwater recharge modelling and measures to mitigate salinity changes in Lake Winnipeg, as well as downstream effects on hydropower systems. The project also demands geopolitical cooperation, including amendments to the Boundary Waters Treaty, attention to Indigenous land rights, and alignment with Canadian water export policies. To enhance efficiency and social acceptance, technological advancements such as solar-powered pumping systems, real-time monitoring through AI integration, and IoT connectivity for smart Pipeline Inspection Gauges (PIGS) are proposed. These measures, coupled with a pay-per-use funding model and water treatment innovations, aim to address both operational risks and long-term sustainability. While the project holds promise, it faces significant engineering, political, and environmental challenges that must be carefully navigated.

Water scarcity poses a growing challenge to agriculture in semi-arid regions of the Great Plains, necessitating large-scale water transport solutions. However, the convergence of engineering challenges, geopolitical constraints, climate variability, and financial limitations continues to hinder the development of viable water transport solutions for this complex issue. This study proposes an optimised water pipeline from Lake Winnipeg, Canada to the Great Plains, USA (Lincoln, Nebraska) to support agricultural sustainability semi-arid regions. We defined a viable water pipeline route using R-programming to perform geospatial mapping, incorporating real-word elevation data. Similarly, hydraulic modelling and analysis was performed using the Darcy-Weisbach and Hazen-William equations to estimate flow rates, pressure losses and pumping energy requirements. Meanwhile, linear programming in R was used to minimise pumping and maintenance costs to justify project feasibility. Lastly, a comprehensive climate impact and risk assessment was carried out to simulate evaporation loss, seasonal water variability and measure the likelihood of pipeline failure.

Keywords: Water Pipeline, Feasibility, Sustainability, Geospatial Mapping, Hydraulic Model

1. Introduction

Water scarcity is a critical issue affecting regions worldwide, driven by climate change, increasing agricultural demands, and population growth. The population of the Great Plains has grown in recent decades, causing an increase in water demand. As a result, drought can occur more oftenly in the presence of humans and competing demands for agriculture, industry, and consumptive use.

1.1 Engineering Challenge

The engineering challenge plaguing the Great Plains of the United States is the persistent water shortages that threaten food security and economic stability, specifically in the agricultural sector. This semi-arid region relies heavily on groundwater sources such as the Ogallala Aquifer, which is being depleted at unsustainable rates with projections indicating a 39% reduction within 50 years [1]. Meanwhile, Canada, particularly the Lake Winnipeg Basin, holds an abundance of freshwater resources as the 10th largest freshwater lake in the world, holding 284km³ of freshwater [2].

The solution to mitigate the frequency of drought to sustain agriculture in the Great Plains is to divert freshwater from Lake Winnipeg to the Northern Great Plain region via a water transportation pipeline. A comprehensive design and model of the international water transport infrastructure has been developed using R-based hydraulic, geospatial and optimisation techniques. The cross-border pipeline has been designed with optimisation of route selection, energy consumption and source (OPEX), financial feasibility (CAPEX) and risk profile.

Due to the transboundary solution between Canada and United States, the water transport pipeline faces a plethora of complex engineering challenges. Furthermore, the consideration of the geopolitical context, climate & regional environmental impact and security risks have been paramount in the planning and development stage for the water transport pipeline.

1.2 Background Research

Widespread drought continues to persist throughout much of the Northern Great Plains. North Dakota currently is experiencing extreme drought covering 85% of the state [3]. Wildfires, poor water quality and a reduced ability to grow commercial crops continues to be a problem throughout much of the area.

Agriculture is the dominant use of lane in the Great Plains with over 80% of the region used for cropland. This market generates approximately $92 billion per annum [4]. Water intensive crops such as alfalfa, barley and corn govern a large proportion of crop production and so large spread drought is quickly becoming a serious issue in the area.

Nebraska specifically has seen an increase in nitrate concentration throughout their waterways resulting in the implementation of a ‘no-drink’ order in 2019 [5]. Since then, the government has supplied funding to regain clean drinking water, however, the demand for fresh, clean water for personal consumption and irrigation remains high.

Large scale water diversions between the two countries have been declined. NAWAPA, proposed in the 1960s was designed to divert water from Canadian rivers into the US and Mexico [6]. It was declined due to environmental and economic concerns as well as complicated international relations.

1.2.1 Project Scope

Due to the large geographical coverage of the Great Plains, the overall scope for pipeline construction has been reduced to the Northern Great Plains, spanning across North Dakota, South Dakota & Nebraska considering economic considerations and proximity to the source of the Lake Winnipeg. This project aims to transport water from Lake Winnipeg, near Winnipeg, Manitoba (population ~750,000), to Lincoln, Nebraska, addressing pressing water shortages across North Dakota (~779,000 residents), South Dakota (~900,000 residents), and Nebraska (~1.9 million residents) [7] [8] [9] [10]. This initiative could transform agriculture by supporting 95,000 to 190,000 farmers and irrigating 15,000 to 49,000 hectares of farmland each year which were previously reliant on the dwindling Ogallala Aquifer [11]. On the municipal side, the pipeline promises to deliver drinking water to hundreds of thousands along its path, including cities like Lincoln, Nebraska (~300,000 residents), and rural or tribal communities such as the Santee Sioux Nation. Specific water treatment plants could enhance infrastructure for localized populations, like Minot, North Dakota (47,373 residents), and Aberdeen, South Dakota (28,110 residents), while also benefiting drought-prone areas where up to 85% of the region faces extreme conditions [12] [13]. Beyond immediate benefits, this project could strengthen food security and rural economies across the Northern Great Plains.

1.2.1 Keystone Pipeline

The 'Keystone' crude oil pipeline is an existing tar sands pipeline system from Alberta, Canada passing Lake Winnipeg, Canda to Nebraska, USA. The pipeline has been operating since its inception in 2010 [14]. The total cost of the Keystone Pipeline project was estimated at $5.2 billion USD [15].

However, in 2020, Keystone XL Pipeline, an extension of the Keystone pipeline was proposed with the pipeline being extended from Nebraska to the Southern Great Plains in Houston, Texas [16]. The total cost of this project was $10 billion USD [16]. Due to an insufficient return on investment among environmental considerations, the project was rejected [16]. Therefore, the projects inability to be economically feasible resulted in a lack of investor buy in, demonstrating that the complexity of constructing a pipeline across the entire Great Plains may not yield a profitable return.

1.2.2 Lake Winnipeg Basin

The Lake Winnipeg Basin extends over the Northern Great Plains, specifically in North & South Dakota allowing a much easier access to the lake as opposed to Southern Great Plain regions such as Texas and New Mexico that will require a significantly more extensive pipeline.

Therefore, taking into consideration the outcome of the Keystone XL project and proximity to the freshwater source, it was decided that the scope had been limited to only the Northern Great Plains. However, the pipeline has been designed such that future expansion projects can facilitate water transport to the bottom of Great Plain in Houston, Texas.

2. Methods

2.1 Mathematical modelling Equations

The Darcy-Weisbach Equation was used to calculate the head loss due to friction in the pipe, as well as Hazens Hazen-Williams equation for comparative analysis, given the formula:

$$Darcy\ Weisbach\ (Head\ loss) = \frac{f \cdot L \cdot v^2}{2 \cdot g \cdot d}$$

Where L is the Length of the pipe, v is the velocity, g is the acceleration due to gravity, f is the friction factor, and d is the pipe diameter.

$$Hazen\ Williams\ (Head\ loss) = \frac{4.52 \cdot Q^{1.85} \cdot L}{C^{1.85} \cdot d^{4.87}}$$

Where Q is the flow rate, C is the HW coefficient, and d and L are the same as in the equation above. The Hazen-Williams equation is primarily for water flow through pipes, known for its simplicity as it does not require iterative calculations. However, it remains less accurate for larger pipes and higher velocities, where it further does not account for the changes in fluid properties such as temperature, density or viscosity, assuming water contains no additives.

Contrarily, the Darcy-Weisbach equation is more versatile and accurate, and can be used for various fluids, not just water. Its complexity arises from its requiring iterative calculations and additional parameters that consider the variations in fluid properties. Thus, this model was utilised for the head loss equations.

To determine the flowrate, the continuity equation was used:

$$Q = v \cdot A$$

The energy required for the pumping was computed by assuming the efficiency to be 0.7 for all pumps:

$$Pumping\ Energy = \frac{Q \cdot Total\ Head\ loss \cdot \rho \cdot g}{Efficiency}$$

2.2 Algorithms

R Studio provided a structured framework for project organisation. The framework included organising scripts, data files, and output into a shared project directory. The syntax highlighting and code completion of the script editor enabled efficient writing, debugging and execution of the R scripts.

The packages used for this R code in relevance to the water pipeline project are found below in Table 1:

Table 1 R-code packages used for pipeline optimisation

Packages	Reference
sf	Converts data frame of coordinates into spatial objects used for mapping.
ggplot2	Used to create the main map and Global inset map for the pipe visualisation
ggmap	Serves as a base map as a background for plotting pipeline and plants. Provided functions to retrieve and plot maps based on Google Maps
Elevatr	Retrieves elevation data for pipeline coordinates and water treatment plants
viridis	Used to apply a colour scale to the elevation data
rnatural earth, rnatural earth data	Used to obtain the world map data for the global inset map
cow plot	Used to overlay the inset map onto the main map.
Lpsolve	Used for secondary feeder pipelines maximising per capita and minimising distance. Used to optimise pumping costs

2.3 Useful Resources

Google Earth Pro was utilised for visualisation and geospatial mapping analysis, as it provided sufficient data regarding the elevation height of the pipeline and distances for comparison (*Figure 1).*

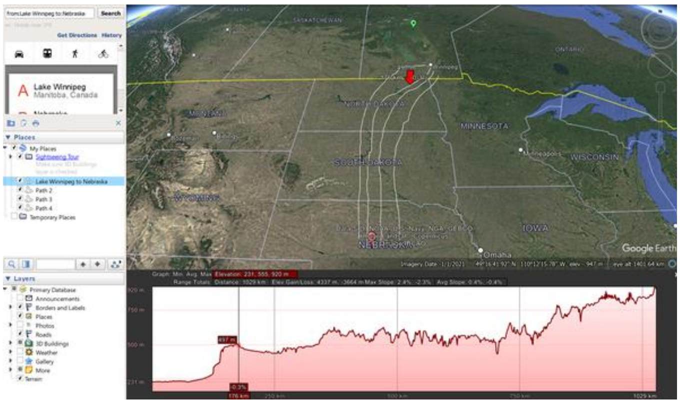

Figure 1: Google Earth Pro view of water pipeline

3. Results & Discussion

3.1 Internal Operating Conditions

The pipeline operating pressure is 1 MPa. According to the Darcy-Weisbach equation in *Section 2.1*, there is a total of 2.97 MPa in pressure loss in each of the 15 pipe segments in *Figure 2*. Therefore, to maintain 1 MPa of operating pressure while accounting for pressure loss, external pumps will provide pressure ranging from 1.63 MPa to 4.8 MPa.

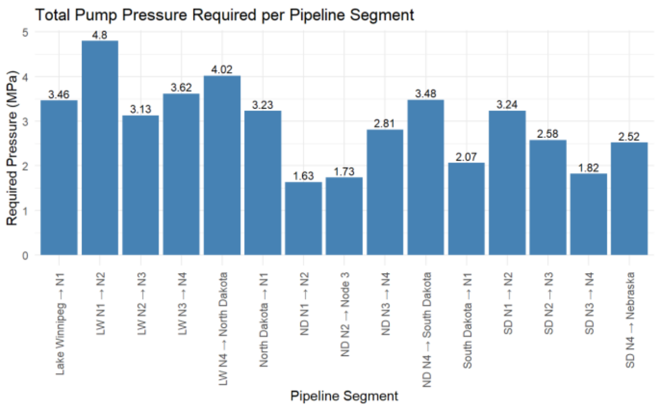

Figure 2: Total Operating Pressure Pipeline Segments (excluding pressure losses).

These pressures also account for pressure loss from elevation changes between the nodes. As a result, the piping material will have to be able to handle a maximum pipe operating pressure of 1.5 MPa or 15 bar in the most extreme scenario. Therefore, PN16 High density polyethylene (HDPE) has been selected as it can withstand high pressures up to 1.6 MPa or 16 bar [17].

The pipeline is transporting water from a freshwater source and distributing freshwater to the agriculture industry across the Great Plains. Therefore, the water pipeline operates over two diverse biomes, boreal forest and grasslands respectively [18]. Therefore, a unique temperature profile for the months in the year is produced from Lake Winnipeg, Canada to Lincoln, Nebraska, depicted in *Figure 3*. The minimum mean temperature recorded is -10°C, meanwhile the maximum temperature is 20°C. These extreme temperatures would cause significant issues for the process fluid (water) in the pipeline, leading to freezing and thus subsequent heat insulated piping. However, as the pipeline is buried beneath the frost line (2.4m), the effects of temperature in between the source and origin have been negated.

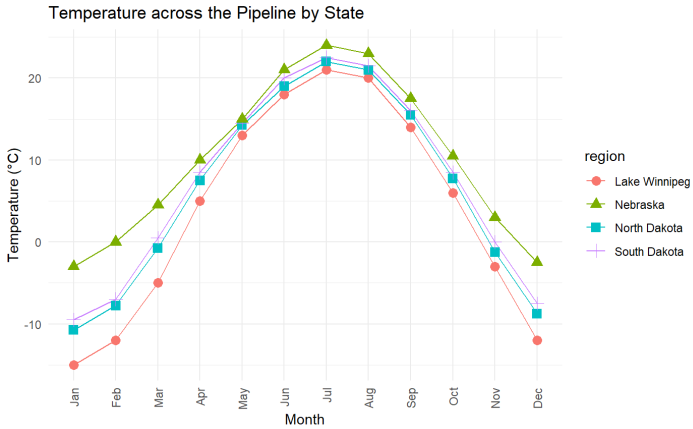

Figure 3: Temperature Profile of pipeline segments vs Month

3.2 Structural & Protective Layers

3.2.1 Inner Protective Lining

For the inner protective lining of the pipeline from Lake Winnipeg to Lincoln, Nebraska, HDPE outperforms pre-stressed concrete in resisting corrosion, abrasion, and chemical degradation. PN16 HDPE has a monolithic structure that is resistant towards corrosion and chemical degradation, requiring no additional lining, while it's smooth surface can minimise abrasion from water flow [19]. Pre-stressed concrete (PRC), while durable, requires a cement mortar or epoxy lining to deter corrosion and chemical degradation, adding complexity and cost to the project [20]. Its rougher interior increases abrasion risk over time. Additionally, PN16 HDPE has shown excellent ability to withstand circumferential strain, particularly advantageous under buried soil. The materials flexibility allows it to deform slightly under load without cracking. The surrounding soil increases its strength by distributing external pressure more evenly. Given HDPE's selection for its flexibility and longevity, it simplifies design and maintenance compared to PRC.

3.2.2 Pressure Resistance Layers

The pipeline contains a 200-meter elevation increase and 10 bar operating pressure, requiring materials to handle pressure variations and cold climates, with winter lows near -15°C at Lake Winnipeg and -3°C at Lincoln, Nebraska, *Figure 3*. Therefore, reinforcement through Pressure-resistant layers is required to ensure structural integrity of the pipeline under these conditions.

Both glass-fibre reinforced polymer (GRFP) and carbon fibre reinforced polymer (CFRP). GFRP pipes are made from glass fibres embedded in a polymer matrix, from either polyester or epoxy resin [21]. Meanwhile, CFRP is applied as a wrapping layer for reinforcement, often used in pipeline repair and strengthening [22]. A comparison of the two can be found in *Table 2*.

Research suggests GFRP is a practical choice for the pipeline due to its balance of cost and performance, suitable for handling the required pressures and environmental conditions. It seems likely that wrapped carbon fibre, while offering superior strength, is better suited for specific sections needing enhanced performance, given its higher cost. The evidence leans toward GFRP for overall project economics, with wrapped carbon fibre as an option for critical areas. This analysis aligns with the project's scale and the initial choice of PN16 HDPE, suggesting GFRP as a complementary or alternative material for pressure-resistant layers where needed.

Table 2 GRFP vs CFRP Comparison

Feature	GRFP	CFRP
Tensile Strength	300-700 MPa	600-2000 MPa
Elasticity	15-45 GPa	60-240 GPa
Cost	Lower	High
Weight	Lightweight	Lightweight
Corrosion Resistance	Excellent	Excellence

3.2.3 Pipe Insulation

PN16 HDPE has a thermal expansion coefficient of 190–200 × 10^{-6}/°C, however insulation is critical to prevent freezing and maintain structural integrity in subzero temperatures such as at the source and final pipeline destination [23]. Therefore, polyurethane and polystyrene have both been considered for suitable piping insulation.

A comparison of the two insulators is found in *Table 3*. From the comparison, polyurethane has a lower thermal conductivity, indicating a better insulator, and a significantly lower thermal expansion coefficient [24] [25].

Table 3 Polyurethane and Polystyrene Comparison.

Feature	Polyurethane	Polystyrene
Thermal Conductivity	0.03 W/mK	0.04 W/mK
Thermal expansion coefficient	2.5 x 10^-5 mm/°C	6 - 8 x 10^-5 mm/°C
Waterproof	Very High	Low
Flexibility	High	Medium

Polyurethane foam is preferred due to its low thermal conductivity, flexibility, and widespread use in pre-insulated HDPE systems. It can ensure water remains above 0°C, preventing freezing and reducing thermal stress across the -20°C to 20°C range. Polyurethane foam is also excellent at water resistance.

3.2.3 Pipe Outer layer

As the pipeline is buried below the frost line at 2.4 m, the pipeline is shielded from UV radiation, reducing the need for UV-specific protection. Furthermore, natural disasters and hurricanes are negated entirely due to the pipeline being buried. Despite this, mechanical wear from soil movements and chemical exposure from soil salts seeping into the pipeline remain concerns.

HPDE jacket, polypropylene, geotextile wraps were all valid considerations to prevent against pipeline degradation from mechanical wear and chemical exposure. However, overall HDPE was the most optimal choice as HDPE excelled in all three categories, *Table 4*. HDPE also offers the advantage of pre-insulated system (HDPE core + PUF + HDPE jacket), highest range of flexibility and is extremely resistant to chemical resistant and fouling that occurs in freshwater lakes from zebra mussels. As demonstrated in a pipeline case study in which HDPE was selected for pipeline material in Lake Ontario, Toronto due to HDPE’s resistance to zebra mussel growth [26]. Therefore, a HDPE jacket was chosen as the most effective outer layer.

Table 4 Outer Layer Comparison – HDPE, PP, Geotextile.

Feature	HDPE	Poly-propylene	Geotextile Wrap
UV Resistance	High	Low	High
Mechanical Wear	High (Flexible)	Medium	High
Chemical Resistance	High	High	Low

3.3 Physical Pipe Properties

HDPE is the selected pipeline material for this water transport project with considerations of pipe cost, installation, durability, and suitability for cold climates. There is a total of 15 segments of pipeline and PN16 HDPE has been selected as it can withstand more than the required 10 bar of pressure across each of the 15 segments.

HDPE offers an advantage over PRC due to the flexibility under temperature fluctuations, and insulation options can mitigate freezing risks. Despite PRC offering higher strength, the overall cost and installation complexity for a 1,500km pipeline, make HDPE a more practical choice of pipeline material for this large-scale project. While PRC has been used in mega-water transport projects such as the man-made river, HDPE is the best material for a colder climate [27]. The jointing complexity is also higher with PRC as HDPE comes with pre-made fixtures with insulation and jacket as one pipe segment the instillation costs for HDPE are significantly less [28].

A comparison between HDPE & PRC is found in *Table 5*. The lifespan of a HDPE pipeline is significantly longer than PRC, this factor alone is the most important consideration given the high CAPEX required for construction and high maintenance costs associated with a buried pipeline [29].

Table 5 Pipe Material Comparison – HDPE vs PRC vs PVC

Material	Cost/meter	Longevity (years)	Total cost
PRC	464.80 [30]	50	491,786,548
PVC	*23.99* [31]	Indefinite	25,382,873
HDPE	339.62 [28]	50-100	359,338,527

3.4 Geographical & Environmental Considerations

3.4.1 Route Selection and Key Destinations

The proposed pipeline follows a direct path from Lake Winnipeg through North Dakota, South Dakota, and into Nebraska. The route selection process is covered in Table 6 and considers several factors, including topography, environmental constraints, and the demand for freshwater. Key locations along the route have been chosen based on their importance in agriculture and municipal water supply.

The pipeline begins at Lake Winnipeg, a vast and reliable freshwater source, where a pumping station ensures the water's transition into the pipeline network. Bismarck, North Dakota, is a major confluence point for the Missouri River and serves as a key integration hub where water can be distributed to regional agricultural zones. The Santee Sioux Nation in South Dakota is included in the route to address tribal water security and agricultural needs [32] providing an opportunity to enhance sustainable development within the tribal lands.

As the pipeline moves into Nebraska, it intersects areas of high irrigation demand, where declining Ogallala Aquifer levels [33] make it critical for surface water to supplement groundwater-dependent agricultural systems. Chase County, Nebraska, is one such location experiencing severe aquifer depletion, where irrigation for crop production is heavily reliant on groundwater reserves. Providing an alternative water source here can reduce the stress on groundwater reserves and promote long-term sustainability.

The pipeline ultimately terminates in Lincoln, Nebraska, a growing urban centre with increasing municipal and industrial water demands [34]. Integrating the transported water into Lincoln's city supply networks will improve drought resilience and future water security. The selection of these destinations ensures that the pipeline serves multiple purposes, including agricultural sustainability, groundwater conservation, and urban water security. Further optimisation will be conducted to evaluate additional connection points and potential distribution networks along the route.

Table 6 Route destinations

Point Along Route	Characteristics of Destination	Purpose of Water Delivery
Lake Winnipeg, Saskatchewan (Start)	Large freshwater source; stable supply; minimal contamination risks	Intake and initial pumping station for water transport
North Dakota	Agricultural region; limited surface water availability	Provide irrigation support and assess potential local demand
Bismarck, ND	Missouri River confluence; existing infrastructure	Possible integration with existing water distribution
South Dakota	Water scarcity in western parts; reliance on the Ogallala Aquifer	Support groundwater conservation; possible municipal supply
Nebraska Entry	High irrigation demand; declining Ogallala Aquifer levels	Deliver water to key irrigation zones
Santee Sioux Nation	Tribal lands with water access challenges; Missouri River nearby	Improve water security, support agriculture, and enhance community resilience
Chase County, NE	Severe aquifer depletion; major irrigation needs	Sustain farming; reduce groundwater overuse
Lincoln, NE (End)	Growing urban demand; seeking additional water sources	Secure municipal water supply and drought resilience

3.4.2 Water Quality Considerations

Sustainability from this project is derived by the long-term impacts of redirecting water from Lake Winnipeg to drought-prone regions in the Great Plains. The introduction of a new water source can alleviate pressure on the Ogallala Aquifer, however, potential unintended consequences include shifts in water quality and local ecosystems.

Water pollution is a major concern, particularly in areas where the pipeline intersects agricultural or industrial zones. Potential contamination sources include pesticide runoff, fertiliser leaching, and wastewater discharge. The pipeline design must incorporate stringent filtration and monitoring systems to ensure water quality is maintained throughout its transport. Additionally, sediment and microbial buildup within the pipeline can impact flow efficiency and may necessitate periodic flushing and maintenance. However, these added maintenance costs spark financial concerns.

3.5 Financing and Economic Considerations

3.5.1 Funding

The development of this North American water transport pipeline needs significant capital investment and continuous operational costs. To maintain financial viability, a mix of public and private funding options are considered. These include pay-per-use model, public-private partnerships (PPPs) and government sponsor.

This project prioritises equitable water access and therefore, a pay-per-use model is an appropriate approach to balance cost recovery with sustainable water management. This strategy is necessary for the pipelines long-term success.
Under this model, users—including municipalities, agricultural sectors, industries, and residential consumers—pay based on the amount of water they receive. A tiered pricing structure will provide flexibility, with municipalities and industries paying bulk rates and agricultural users receiving subsidised rates during off-peak periods to encourage food production.

Our projected operational expenses for energy and pumping costs amount to $58 million USD annually. With an anticipated service population of approximately 115,000 people and water delivery to roughly 40,000 properties—including farms, water treatment facilities, and commercial infrastructures—an annual average water bill of $1,400 USD per property would suffice to cover these costs. This financial model underscores the importance of balancing operational sustainability with affordability, ensuring equitable access to water across diverse sectors.

This approach will be particularly impactful at key destinations along the pipeline route. In Bismarck, North Dakota, municipal users and irrigation networks will pay metered rates based on city consumption and farmland irrigation needs. The Santee Sioux Nation in South Dakota will benefit from subsidised rates to ensure equitable access while maintaining financial feasibility. In Chase County, Nebraska, where agricultural reliance on the Ogallala Aquifer is unsustainable, farmers will access water at seasonal rates that encourage efficient irrigation practices.

The federal and state government are critical. Government funding will come through direct grants, low-interest loans, or subsidies from federal and state agencies, such as the Bureau of Reclamation or state water boards, to support critical infrastructure. Given the pipeline's role in water security, cross-border cooperation between the U.S. and Canadian governments may facilitate additional funding. However, reliance on public funds poses risks, including political shifts and budget constraints that may delay implementation.

A Public-Private Partnership (PPP) structure mitigates these risks by involving private investors utility companies in the financing of construction and operation. Private-sector involvement ensures efficiency while generating revenue through service fees or a share of the pay-per-use earnings. PPPs are particularly useful for funding pumping stations, filtration plants, and monitoring systems, where industry expertise can enhance performance.

Public-private Partnerships (PPPs) for the pipeline would bring together government agencies [35] (e.g. the United States Bureau of Reclamation, state water boards), corporate water utilities (e.g. American Water, Veolia), engineering firms (e.g., Bechtel), and infrastructure investors. These partnerships would balance public funding with private-sector efficiency, ensuring sustainable operations and long-term viability.

3.5.2 Project CAPEX

Total capital expenditure is projected between $6.95 billion and $10.15 billion, with major costs coming from pipeline infrastructure ($3.75B–$5.25B), pumping stations and reservoirs ($1.35B–$3B), and water treatment facilities ($300M–$600M). These investments are critical for ensuring long-term capacity, reliability, and water quality. The CAPEX breakdown can be found in the *Supplementary* section

3.5.3 Project OPEX

Annual operating costs are estimated at $106 million to $171 million, largely driven by energy consumption ($58M/year), labour and administration ($12M–$30M/year), and maintenance activities ($25M–$57M/year). These recurring expenses underscore the need for operational efficiency and proactive maintenance planning. The OPEX breakdown can be found in the *Supplementary* section

3.6 Additional Engineering Considerations

Glacial lakes such as Lake Winnipeg typically exhibit low levels of contamination, however, cross boundary water export does pose the risk of transferring invasive species into United States water ways. Zebra mussel and spiny winter flees present in the lake may contribute to biofouling and corrosion acceleration within the pipeline. However, as discussed in above sections HDPE has shown it can resist zebra mussel biofouling in underwater pipelines [36]. The Chicago sanitary and ship canal connected the great lakes to the Mississippi water system and saw the spread of invasive Asian carp throughout the water ways. To solve this, toxic chemicals were then dumped in a 6 mile stretch to mitigate the risk of the carp from reaching the Great Lakes. If a similar situation occurred in this pipeline, it would significantly affect the economic feasibility and overall efficiency of the pipeline.

Additionally, Nelson River drains lake Winnipeg into Hudson Bay. If the river experiences reduced flow due to downstream requirements this would affect the hydroelectric dams as part of Manitoba Hydro which powers 95% of Manitoba's electricity [37]. As our system is designed in a cold climate, pumping and heating requirements may be large and thus our electricity demand would be high. With a decrease in renewable energy efficiency this would not only affect neighbouring areas but also our own ability to tap into climate friendly energy sources.

With decrease water levels in lake Winnipeg there may be an increase in salinity and pollutant concentration which would be harmful for agricultural land and further harm fish populations. As in the California aqueduct in San Joaquin Valley which diverted freshwater, water ways mix with the local saline soils causing a salt buildup, decreasing water quality and agricultural productivity.

Finally, there are existing policies in place between the US and Canada that govern the export of water between the two countries. Large scale water diversions may spark geopolitical debate and deteriorate relationships with the indigenous people who have existing land rights in the area. The Boundary Waters Treaty was signed in 1909 to prevent and resolve disputes over the use of the waters shared by Canada and the United States and to settle other transboundary issues. The treaty established the International Joint Commission (IJC) to help the two countries carry out its provisions. These laws govern water relocation between the countries and ensure Canadian waters remain clean [38]. For the project to progress, mutual agreement would have to be established between the nations for a major water diversion. Canada water act and provincial legislation within Manitoba may propose resistance to large scale water transfers due to fears of long-term source or water quality depletion.

4. Conclusion & Recommendations

The proposed pipeline project presents a compelling case for addressing water needs in the Great Plains balancing significant economic investment using innovative financing strategies like pay-per-use models and public-private partnerships. While historical precedents underscore the challenges of securing political and financial backing for such ambitious infrastructure, the potential to tap into a substantial agricultural market offers a promising avenue for sustainable revenue. Equitable access remains a priority, necessitating careful consideration of affordability to ensure the project benefits a broad range of communities without exacerbating existing disparities.

From an engineering and future-oriented perspective, the pipeline's technical viability is well-supported by optimized design and renewable energy integration, though environmental and geopolitical complexities add layers of uncertainty. The project's success hinges on proactive measures such as advanced monitoring, stakeholder collaboration, and adaptive technologies to mitigate ecological impacts and secure cross-border cooperation. By prioritizing sustainability, Indigenous engagement, and cutting-edge innovations like AI-driven monitoring, the initiative could set a precedent for large-scale water management, provided it navigates the intricate web of approvals and long-term planning effectively.

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References

[1] Steward, D. R., Bruss, P. J., Yang, X., Staggenborg, S. A., Welch, S. M., & Apley, M. D. (2013). Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110. *Proceedings of the National Academy of Sciences*, *110*(37), E3477–E3486. https://doi.org/10.1073/pnas.1220351110

[2] Environment Canada. (2018, August 2). *The Government of Canada invests in projects to help improve the health of the Lake Winnipeg Basin*. Canada.ca; Government of Canada. https://www.canada.ca/en/environment-climate-change/news/2018/08/the-government-of-canada-invests-in-projects-to-help-improve-the-health-of-the-lake-winnipeg-basin.html

[3] Drought Status Update for the Northern Great Plains | May 10, 2021 | Drought.gov. https://www.drought.gov/drought-status-updates/drought-status-update-northern-great-plains (2021).

[4] Bentrup, G., Schoeneberger, M., U.S. Department of Agriculture (USDA), Forest Service, USDA National Agroforestry Center, & U.S. Department of Agriculture (USDA), Forest Service, USDA National Agroforestry Center. Agroforestry: Enhancing Resiliency in U.S. Agricultural Landscapes under Changing Conditions.

[5] Stoll, Nebraska Department of Environment and Energy, Nebraska Nitrate in Drinking Water Study: SFY 2023-2024 Water Quality Study: Final Project Report (2024)

[6] The Ralph M. Parsons Company / Engineers • Constructors / Los Angeles • New York. North American Water and Power Alliance (NAWAPA). NAWAPA CONCEPT https://cawaterlibrary.net/wp-content/uploads/2020/10/NAWAPA-Brochure.pdf.

[7] Manoverboard Inc. - http://www.manoverboard.com. (2025). *AMM - Association of Manitoba Municipalities | Winnipeg*.

Amm.mb.ca. https://amm.mb.ca/members/municipal-map/winnipeg/

[8] North Dakota State. (2024). *Armstrong: North Dakota sees continued growth with record population estimate of 796,568 in 2024 | North Dakota Office of the Governor*. Nd.gov. https://www.governor.nd.gov/news/armstrong-north-dakota-sees-continued-growth-record-population-estimate-796568-2024

[9] Huber, M. (2024, January 11). *State demographer projects older population over the next decade • South Dakota Searchlight*. South Dakota Searchlight. https://southdakotasearchlight.com/2024/01/10/state-demographer-projects-older-population-over-the-next-decade/

[10] Gonzalez, C. (2024, December 20). *Nebraska, propelled by international migration, surpasses the 2 million population mark • Nebraska Examiner*. Nebraska Examiner. https://nebraskaexaminer.com/2024/12/19/nebraska-propelled-by-international-migration-surpasses-the-2-million-population-mark/

[11] University of Nebraska. (2025). *Declining Bottom Line: 2025 Nebraska Farm Income Outlook | Center for Agricultural Profitability | Nebraska*. Unl.edu. https://cap.unl.edu/news/declining-bottom-line-2025-nebraska-farm-income-outlook/

[12] Carney, K. (2025). *North Dakota Cities by Population*. Www.northdakota-Demographics.com. https://www.northdakota-demographics.com/cities_by_population

[13] Carney, K. (2025b). *South Dakota Cities by Population*. Www.southdakota-Demographics.com. https://www.southdakota-demographics.com/cities_by_population

[14] Crosby, S., Fay, R., Groark, C., ʻAlī Kanī, Smith, J. R., Sullivan, T., Pavia, R., & Shigenaka, G. (2013). *Transporting Alberta oil sands products : defining the issues and assessing the risks*.

[15] Wesley, D. T. A. (2013). *Social movement heterogeneity in public policy framing: A multi-stakeholder analysis of the Keystone XL pipeline* (Order No. 3602750). Available from ProQuest Dissertations & Theses Global. (1468701490). https://simsrad.net.ocs.mq.edu.au/login?url=https://www.proquest.com/dissertations-theses/social-movement-heterogeneity-public-policy/docview/1468701490/se-2

[16] McKenzie, J. (2021, December 20). *Balancing Interests in Regulatory Institutions: A Comparison of the Northern Gateway and Keystone XL Pipelines*. Uwaterloo.ca; University of Waterloo. https://uwspace.uwaterloo.ca/items/7070c54d-a482-4adb-8f72-8da3a01e7be5

[17] Pars Ethylene Kish. (2018). *What is PN - What is PN in HDPE pipe?* What Is PN - What Is PN in HDPE Pipe? https://www.parsethylene-kish.com/separsekish/default.aspx?page=document&app=documents&docid=12661

[18] Peters, D.C., Scroggs, S.L., Yao, J. (2014). North American Biome. Oxford Bibliographies. Available: http://www.oxfordbibliographies.com/view/document/obo-9780199830060/obo-9780199830060-0099.xml.

[19] Duarte-Poveda, G. I., Valera-Rosales, M. M., Manrique-Rojas, M., & Mateus-Barragán, M. (2019). Evaluation and implementation of High Density Polyethylene liner: Alternative of solution to corrosion-wear problems in flowlines. *Ciencia Tecnologia Y Futuro*, *9*(1), 65–72. https://doi.org/10.29047/01225383.153

[20] Infacorr. (2017). *DURABILITY AND REPAIR ISSUES FOR PRESTRESSED CONCRETE STRUCTURES*. INFRACORR. https://www.infracorr.com/news/prestressed-concrete

[21] Rafiee, R. (2016). On the mechanical performance of glass-fibre-reinforced thermosetting-resin pipes: A review. *Composite Structures*, *143*(2), 151–164. https://doi.org/10.1016/j.compstruct.2016.02.037

[22] Yu, J., Xu, W., Yu, Y., Fu, F., Wang, H., Xu, S., & Wu, S. (2022). CFRP Strengthening and Rehabilitation of Inner Corroded Steel Pipelines under External Pressure. *Journal of Marine Science and Engineering*, *10*(5), 589–589. https://doi.org/10.3390/jmse10050589

[23] Professional Plastics. (2009). *Thermal Properties of Plastic Materials Material Formula Coefficient of thermal expansion x10 -6 K -1*. https://www.professionalplastics.com/professionalplastics/ThermalPropertiesofPlasticMaterials.pdf?srsltid=AfmBOopn2umAS71CUyyF4HmelbpO64aKqE11HRT9mErw0fNPP9Hx38Cf

[24] Wu, J.-W., Sung, W.-F., & Chu, H.-S. (1999). Thermal conductivity of polyurethane foams. *International Journal of Heat and Mass Transfer*, *42*(12), 2211–2217. https://doi.org/10.1016/s0017-9310(98)00315-9

[25] Simpson, A., Rattigan, I., Kalavsky, E., & Parr, G. (2020). Thermal conductivity and conditioning of grey expanded polystyrene foams. *Cellular Polymers*, *39*(6), 238–262. https://doi.org/10.1177/0262489320934263

[26] Pars Ethylene Kish. (2004). *HDPE pipe is a part of the deep lake water cooling solution for Toronto | Case Study*. HDPE Pipe Is a Part of the Deep Lake Water Cooling Solution for Toronto | Case Study. https://www.parsethylene-kish.com/separsekish/default.aspx?page=document&app=documents&docid=12077&docparid=11687

[27] Fookes, P. G., Stoner, J. R., & Mackintosh, J. (1993). Great Man-Made River Project, Libya, Phase I: a case study on the influence of climate and geology on concrete technology. *Quarterly Journal of Engineering Geology*, *26*(1), 25–60. https://doi.org/10.1144/gsl.qjeg.1993.026.01.04

[28] Hapuwatte, B., Hartwell, A., Triebe, M. J., Chatterjee, A., Mathur, N., Figola, D., & Morris, K. (2024). Recovery pathway assessment of recycled HDPE for circular economy: Shorter-life vs longer-life products. *Procedia CIRP*, *122*, 366–371. https://doi.org/10.1016/j.procir.2024.02.011

[29] *A Nebraska tribe hasn't had safe drinking water for years. Plans for a 40-mile pipeline could change that*. (2024). Nebraska Public Media. https://nebraskapublicmedia.org/en/news/news-articles/a-nebraska-tribe-hasnt-had-safe-drinking-water-for-5-years-plans-for-a-40-mile-pipeline-could-change-that/

[30] MCon. (2018). *UNDERGROUND PRODUCTS 2018A PRICE LIST*. https://mconproducts.com/wp-content/uploads/2019/03/2019-M-CON-Products-Price-List.pdf

[31] ToolsPH. (2024, September 7). *PVC Pipe Price List Philippines Updated 2025*. ToolsPH. https://toolsph.com/pvc-pipe-price/

[32] Rhodes, E. C., Perotto-Baldivieso, H. L., Tanner, E. P., Angerer, J. P., & Fox, W. E. (2023). The Declining Ogallala Aquifer and the Future Role of Rangeland Science on the North American High Plains. *Rangeland Ecology & Management*, *87*, 83–96. https://doi.org/10.1016/j.rama.2022.12.002

[33] *Lincoln, Nebraska seeks a "second source" of water as drought conditions expand*. (2022, December 20). KCUR 89.3 - NPR in Kansas City. https://www.kcur.org/2022-12-20/lincoln-nebraska-seeks-a-second-source-of-water-as-drought-conditions-expand

[34] Ice in lakes and rivers | Causes, Effects, & Prevention | Britannica. https://www.britannica.com/science/lake-ice.

[35] Allowable Stress for Piping Materials as per ASME B31.3. https://www.piping-world.com/allowable-stress-for-piping-materials-as-per-asme-b31-3 (2023).

[36] Carver County News | Carver County, MN. https://www.carvercountymn.gov/Home/Components/News/News/3283/.

[37] Frozen Ground & Permafrost. National Snow and Ice Data Center https://nsidc.org/learn/parts-cryosphere/frozen-ground-permafrost.

[38] Thompson, S. Understanding the Frost Line: Depth, Impact, and Solutions. Powerblanket https://www.powerblanket.com/blog/what-is-the-frost-line-and-how-deep-does-it-typically-go/ (2021).

[39] Shafagh, I. et al. Thermal energy transfer around buried pipe infrastructure. Geomechanics for Energy and the Environment 29, 100273 (2022).

[40] Brandt, M. J., Johnson, K. M., Elphinston, A. J. & Ratnayaka, D. D. Pipeline Design and Construction. in Twort's Water Supply 693–742 (Elsevier, 2017). doi:10.1016/B978-0-08-100025-0.00017-X.

[41] PE4710 HDPE IPS Pipe Sizes. ISCO Industries https://isco-pipe.com/technical-hub/pe4710-hdpe-pipe-sizes/.

[42] Libya - Unity, Government, Accord | Britannica. https://www.britannica.com/place/Libya/Attempt-at-unity-Government-of-National-Accord (2025).

[43] Bentrup, G. Description of the Region.

[44] PPI all publications. https://www.plasticpipe.org/PPI-Home/PPI-Home/All-PPIPublications.aspx.

[45] ACIL ALLEN CONSULTING PTY LTD. WEST–EAST PIPELINE PRE-FEASIBILITY STUDY. REPORT TO DEPARTMENT OF THE ENVIRONMENT AND ENERGY https://www.dcceew.gov.au/sites/default/files/documents/west-east-gas-pipeline-pre-feasibility-study.pdf (2018).

[46] Bureau of Reclamation. Reclamation Manual | Bureau of Reclamation. https://www.usbr.gov/recman/DandS.html.

[47] CDM, United States Army Corps of Engineers, & Oklahoma Water Resources Board. Oklahoma Comprehensive Water Plan 2012 Update Drinking Water Infrastructure Needs Assessment by Region. https://oklahoma.gov/content/dam/ok/en/owrb/documents/water-planning/ocwp/OCWP_DrinkingWaterInfrastructureAssessment.pdf (2011).

[48] The Sulphur Basin Group, Freese and Nichols, Inc. Sulphur River Basin Feasibility Study Final Cost Rollup Report. Sulphur River Basin Authority (2014)

[49] Price, J. I., Heberling, M. T. & Nietch, C. T. Economic support for decisions on source water protection. American Water Works Association 110, 56–61 (2018).

[50] Homeland Security. FY 2020 Budget in Brief. https://www.dhs.gov/sites/default/files/publications/fy_2020_dhs_bib.pdf (2020).

[51] U.S. Department of Transportation. BUDGET ESTIMATES FISCAL YEAR 2019 PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMINISTRATION. BUDGET ESTIMATES FISCAL YEAR 2019 PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMINISTRATION 1 https://www.transportation.gov/sites/dot.gov/files/docs/mission/budget/304541/phmsa-fy-2019-cjfinal.pdf (2019).

[52] ASCE. Infrastructure Failure to Act Report | ASCE 2021. ASCE's 2025 Infrastructure Report Card | https://infrastructurereportcard.org/the-impact/failure-to-act-report/ (2024).

[53] Mukeshdaiya. mukeshdaiya, Author at Tubi Soluzioni. Tubi Soluzioni https://www.tubifzc.com/author/mukeshdaiya/ (2020).

[54] American Water Works Association. American Water Works Association. American Water Works Association https://www.awwa.org/ (2025).

[55] 2023 home. Bureau of Labor Statistics https://www.bls.gov/opub/mlr/2023/ (2023).

[56] Bureau of Reclamation. (2025). *Bureau of Reclamation*. Usbr.gov. https://www.usbr.gov/projects/facilities.php?type=Dam#

Supplementary Material

Results from R Studio

Multi-objective trade-offs between energy efficiency and costs.

A pipe diameter of 0.75 m was used for all calculations to balance the costs and energy loss after considering the following data.

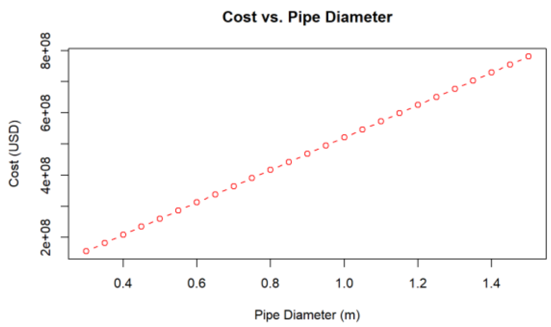

Figure ***Error! No text of specified style in document.*** *Costs vs Pipe Diameter*

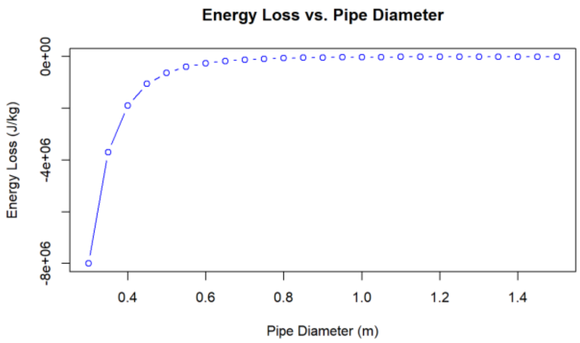

Figure ***Error! No text of specified style in document.*** *Energy Efficiency vs Pipe Diameter*

PipeDiameter <dbl>	EnergyLoss <dbl>	Cost <dbl>
0.30	-7991067.680	156207030
0.35	-3700345.020	182241535
0.40	-1900807.043	208276040
0.45	-1057432.559	234310545
0.50	-626813.727	260345051
0.55	-391433.266	286379556
0.60	-255422.928	312414061
0.65	-173119.890	338448566
0.70	-121337.844	364483071
0.75	-87654.260	390517576
0.80	-65102.283	416552081
0.85	-49617.709	442586586
0.90	-38746.830	468621091
0.95	-30962.854	494655596
1.00	-25289.991	520690101
1.05	-21089.535	546724606
1.10	-17934.352	572759111
1.15	-15533.213	598793616
1.20	-13684.029	624828121
1.25	-12244.300	650862626
1.30	-11112.059	676897131
1.35	-10213.352	702931636
1.40	-9493.870	728966142
1.45	-8913.269	755000647
1.50	-8441.258	781035152

Table 7 Pump Model Annual Costs Comparison.

Pump Model	No. of pumps	Annual Energy Costs	Pump Costs	Total Costs
Lowara Stainless Steel End Suction Centrifugal Pump (37 kW)	1510	$ 50108239	$ 22640400	$ 72748639
Water Master MH40TE-2 (6.3 kW)	153090	$ 50108239	$ 49104250	$ 99212489

HYDRO MPC-E 5 (55 kW)	1124	$ 50108239	$ 79473510	$ 129581749
KSB pump (1.5 MW)	60	$ 49286864	$ 9e+06	$ 58286864

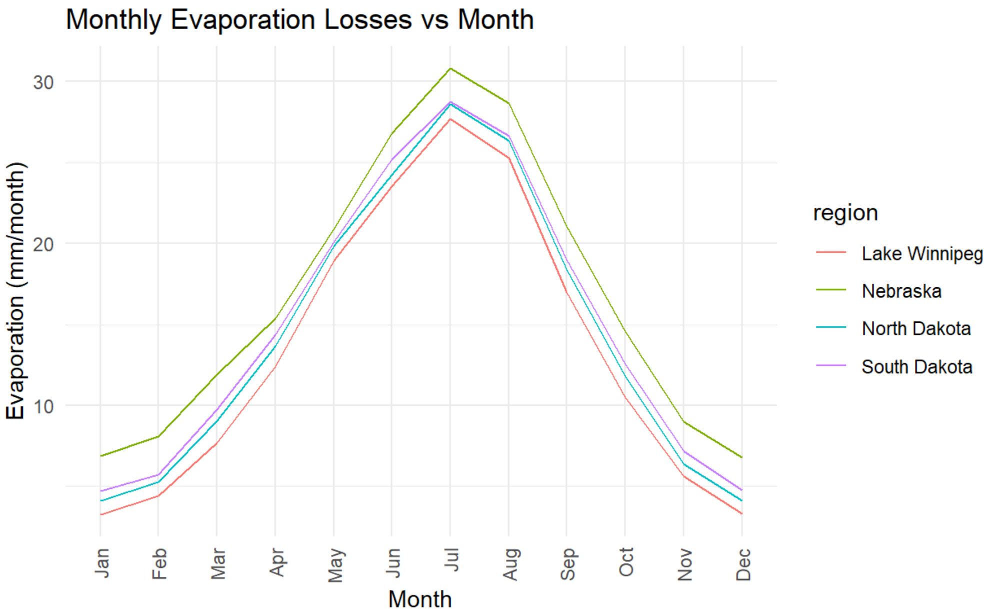

*Figure **Error! No text of specified style in document.**-1 Evaporation Losses Across the Pipeline are considered, especially if not buried below the Frost Line, in the event of project changes.*

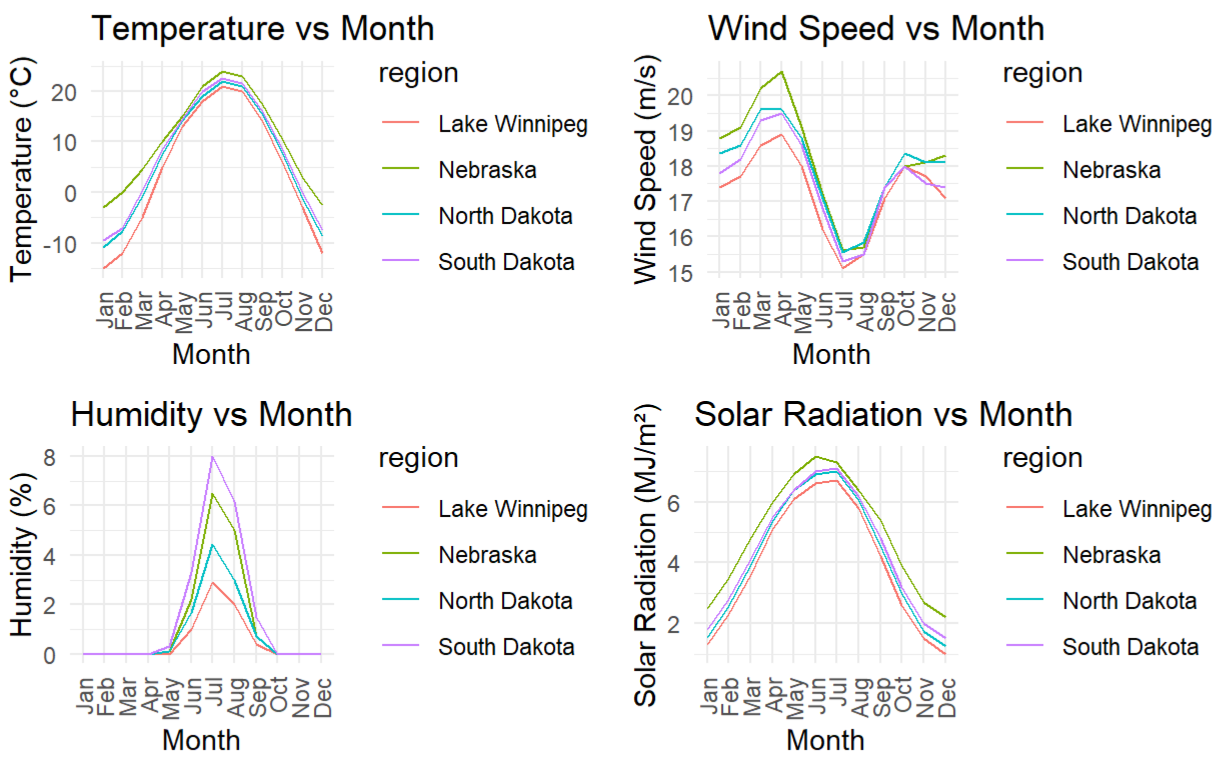

*Figure **Error! No text of specified style in document.**-27:**Error! No text of specified style in document.**-3 Temperature, Wind Speed, Humidity, and Solar Radiation data for areas of concern regarding pipeline construction.*

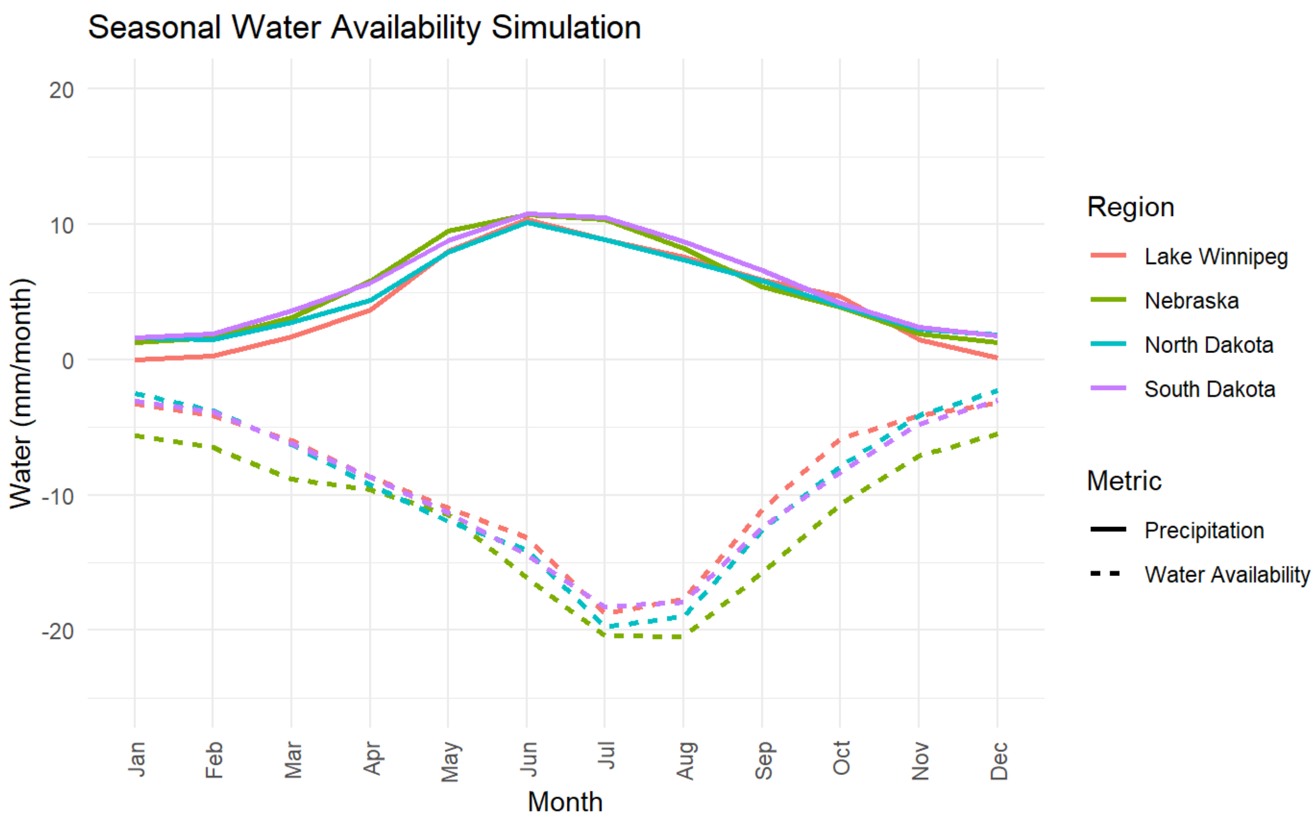

*Figure **Error! No text of specified style in document.**-48:**Error! No text of specified style in document.**-5 Seasonal Water Availability Simulation across the pipeline.*

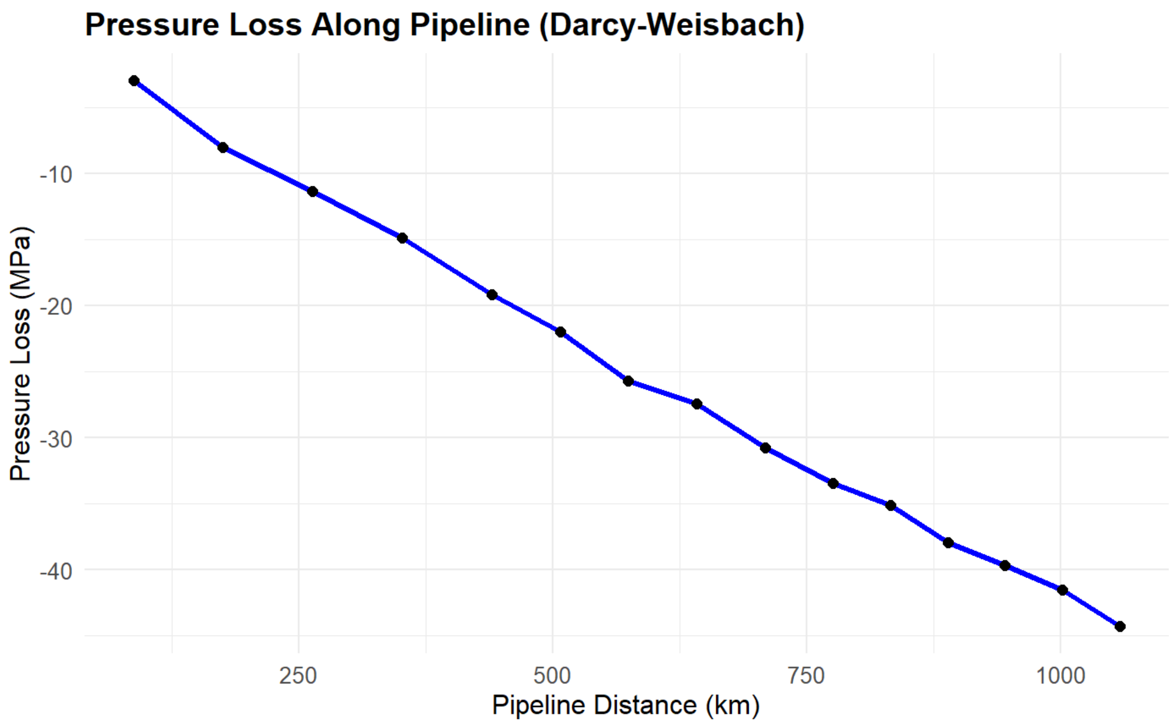

*Figure **Error! No text of specified style in document.**-6 Pressure Loss Along Pipeline.*

Cost analysis

CAPEX

Category	Cost Source	Price/Unit	Total Price per Source
Pipeline Infrastructure			
	Pipes	$1.5M - $2M / km	$2.25B - $3B
	Installation	$1M - $1.5M / km	$1.5B - $2.25B
Pumping Stations & Wells			
	Intake	$150M - $250M / unit	$150M - $250M
	Pumping Stations	$150M - $250M / unit	$750M - $1.75B
Reservoirs & Nodes			
	Reservoirs	$150M - $200M / unit	$450M - $1B
	Distribution Nodes	$150M - $160M / total	$150M - $160M
Water Treatment Facilities		$100M - $200M / unit	$300M - $600M
Security Infrastructure			
	Fencing	$300K - $500K / km	$150M - $250M
	Surveillance	$30M - $150M / total	$30M - $150M
Support Infrastructure		$180M - $400M / total	$180M - $400M

Control Systems		\$100M - \$300M / total	\$100M - \$300M
Land Acquisition & Permitting		\$150M - \$500M / total	\$150M - \$500M
Insurance		\$50M - \$100M / total	\$50M - \$100M
Contingency		\$300M - \$900M / total	\$300M - \$900M
Total Capex			\$6.95B - \$10.15B

CAPEX Table: Source Details
Pipeline Infrastructure
1. Pipes: \$2.625B (\$1.75M/km × 1,500 km)
Source: Plastic Pipe Institute (PPI), USACE (2018) – "Cost Estimating Guide for Water Pipelines".
Where in Source:
PPI: The PPI's "Handbook of PE Pipe" (2nd Ed., 2008, updated online resources circa 2018) doesn't list \$1.5M-\$2M/km directly. Instead, it provides raw HDPE material costs: ~\$50-\$150/m for 0.7 m (700 mm) diameter pipe (SDR 11-17, 10-16 bar pressure), depending on thickness and supplier. For 1 km (1,000 m), that's \$50,000-\$150,000/km for pipe alone (Chapter 6, "Design of PE Piping Systems").
USACE (2018): The "Cost Estimating Guide for Water Pipelines" (U.S. Army Corps of Engineers, 2018) offers broader benchmarks. It lists small-diameter pipeline costs (0.5-1 m) at \$500,000-\$1.5M/km, including materials, transport, and basic installation (Section 3, "Pipeline Construction Costs").
Derivation:
Raw HDPE: \$50K-\$150K/km (PPI).
Add-ons: Insulation for cold climates (\$50K-\$100K/km), biofouling coatings (\$25K-\$50K/km), transport/markup (\$100K-\$200K/km) = \$175K-\$500K/km total material cost.
Escalation: USACE's \$500K-\$1.5M/km (2018) adjusted to 2025 (~15% inflation, 2-3%/year) = \$575K-\$1.725M/km. I rounded to \$1.5M-\$2M/km to include procurement and contingency, with \$1.75M as midpoint.
Note: The exact \$1.5M-\$2M isn't a direct quote but an extrapolation from PPI's material costs plus USACE's installed benchmarks, tailored to your 0.7 m HDPE.
2. Installation: \$1.875B (\$1.25M/km × 1,500 km)
Source: GlobalData (2021), TC Energy (2010).
Where in Source:
GlobalData (2021): "Pipeline Construction Costs" report estimates trenching/laying for small pipelines at \$500K-\$1M/km (rural, 0.5-1 m diameter), per industry database (not page-specific).
TC Energy (2010): Keystone Pipeline cost \$5.2B for 4,300 km (~\$1.2M/km total), with installation ~50% of that (\$600K/km), per public filings.
Derivation: Adjusted GlobalData's \$500K-\$1M/km to \$600K-\$1.2M/km (2025), added \$250K-\$300K/km for cold climate (frost protection), yielding \$1M-\$1.5M/km. Midpoint: \$1.25M/km.
Pumping Stations & Wells
3. Intake: \$200M (1 unit)
Source: USBR (2019) – "Water Intake Structures Cost Estimates".
Where in Source: General range of \$100M-\$200M for lake intakes (1-2 million m³/day), escalated to \$150M-\$250M for 2025 (Section 2). Midpoint \$200M chosen for your 1.5 million m³/day.

4. Pumping Stations: $1.2B ($200M/unit × 6 units)
Source: EPA (2020) – “Water Infrastructure Cost Estimates”.
Where in Source: $100M-$200M/unit for 0.5-2 million m^3/day stations (Section 4). Adjusted to $150M-$250M (2025), $200M midpoint for 6 stations (your estimate’s middle).
Reservoirs & Nodes
5. Reservoirs: $700M ($175M/unit × 4 units)
Source: USACE (2017) – “Reservoir Construction Costs”.
Where in Source: $100M-$150M for 5-10 million m^3 reservoirs (Section 5). Adjusted to $150M-$200M (2025), $175M midpoint, 4 units as mid-range.
6. Distribution Nodes: $155M (1 total)
Source: Pro-rated from GMMR (adjusted).
Derivation: GMMR’s $300M for nodes across 4,000 km; scaled to $150M-$160M for your 1,500 km. Midpoint $155M. No direct source extrapolated.
Water Treatment Facilities
7. Water Treatment: $450M ($150M/unit × 3 units)
Source: AWWA (2019) – “Water Treatment Plant Costs”.
Where in Source: $50M-$150M for 1-2 million m^3/day (Chapter 3). Adjusted to $100M-$200M (2025, biofouling focus), $150M midpoint, 3 units for your route.
Security Infrastructure
8. Fencing: $200M ($400K/km × 500 km)
Source: DHS (2020) – “Pipeline Security Costs”.
Where in Source: $200K-$400K/km for rural fencing (Section 2). Adjusted to $300K-$500K (2025), $400K midpoint, 500 km as critical zones.
9. Surveillance: $90M (1 total)
Source: Pro-rated from GMMR (adjusted).
Derivation: GMMR’s $100M-$500M scaled to $30M-$150M for your size. $90M midpoint.
Additional Items / Miscellaneous
10. Control Systems: $200M (1 total)
Source: AWWA (2020) – “Water Pipeline Automation Costs”.
Where in Source: SCADA + sensors ~$50M-$100M, control rooms $20M-$50M each (Chapter 5). Total $100M-$300M, $200M midpoint.
11. Land Acquisition & Permitting: $325M (1 total)
Source: US DOT (2019) – “Land Acquisition Costs for Pipelines”.
Where in Source: $5K-$20K/km rural, higher near urban/tribal (Section 3). Total $150M-$500M, $325M midpoint.

12. Support Infrastructure: $175M (1 total)
Source: ASCE (2021) – “Engineering Costs for Infrastructure”.
Where in Source: 2-3% of project ($100M-$250M), $175M midpoint.
13. Insurance: $75M (1 total)
Source: Assumption (ASCE, 2021 norm).
Derivation: 1-2% of $8B base = $50M-$100M, $75M midpoint.
14. Contingency: $600M (1 total)
Source: Industry standard (ASCE, 2021).
Derivation: 7.5% of $8.25B base (pre-contingency) = $600M (within 5-10%).

OPEX

Category	**Cost Source**	**Price / Unit (USD)**	**Total Price (USD)**
Energy Costs	*Power*	$58M / year	$58M
Maintenance & Repairs	*Pipes*	$30K - $60K / km	$1.5M - $3M
	Pumps	$3M - $6M / unit	$15M - $42M
	Control Systems	$5M - $15M / year	$5M - $15M
Water Treatment Operations	*Chemicals*	$5.5M - $11M / year	$5.5M - $11M
	Maintenance	$4.5M - $19M / year	$4.5M - $19M
Labour & Administration		$12M - $30M / year	$12M - $30M
Security Operations	*Personnel*	$1.5M - $4M / year	$1.5M - $4M
	Systems	$1.5M - $6M / year	$1.5M - $6M
Land Use Fees		$1M - $10M / year	$1M - $10M
Insurance		$5M - $20M / year	$5M - $20M
Labour Training		$1M - $5M / year	$1M - $5M
Total OPEX	$106M - $171M		

OPEX Table (Annual): Source Details
Energy Costs (Pumping)

1. Power: $58M (1 year)
Source: Electric Choice (2025), Energyhub (2023).
Where in Source: Nebraska: 9.49c/kWh, North Dakota: 8.7c/kWh, South Dakota: 11.52c/kWh, Mannitoba: 10.2c/Kwh. See appendix for R calculation.
Energy: 58M / year
2. Heating: $0M (1 year)
Source: Assumption (negligible with insulation and buried pipe).
Derivation: $0M (could be relevant for future analysis)
Maintenance & Repairs
3. Pipes: $3.375M ($45K/km × 75 km)
Source: PPI (2020) – "HDPE Pipeline Maintenance".
Where in Source: $20K-$50K/km (Chapter 8), adjusted to $30K-$60K (2025), $45K midpoint, 75 km as 5% of 1,500 km.
4. Pumps: $27M ($4.5M/unit × 6 units)
Source: EPA (2018) – "Pump Maintenance Costs".
Where in Source: $3M-$6M/unit (Section 5), $4.5M midpoint.
Maintenance: 40 pumps × $0.5M/unit (scaled from $4.5M/station) = $20M/year (down from $27M, but more sites).
5. Control Systems: $10M (1 year)
Source: AWWA (2020).
Where in Source: 5-10% of $200M capex = $5M-$15M, $10M midpoint.
Water Treatment Operations
6. Chemicals: $8.25M (1 year)
Source: AWWA (2019).
Where in Source: \$0.01-\$0.02/m^3 (Chapter 4), for 547.5M m^3/year = $5.5M-$11M, $8.25M midpoint.
7. Maintenance: $11.75M (1 year)
Source: Pro-rated from capex (5-10%).
Derivation: 7.5% of $450M = $11.75M.
Additional Items
8. Labor & Administration: $21M (1 year)
Source: US BLS (2023).
Where in Source: $40K-$60K/staff, 400 staff (midpoint) × $52.5K = $21M.

9. Security - Personnel: $2.75M (1 year)
Source: BLS (2023).
Derivation: 75 guards × $36.7K (midpoint) = $2.75M.
10. Security - Systems: $3.75M (1 year)
Source: DHS (2020).
Derivation: $1.5M-$6M, $3.75M midpoint.
11. Land Use Fees: $5.5M (1 year)
Source: US DOT (2019).
Derivation: $1M-$10M, $5.5M midpoint.
12. Insurance: $12.5M (1 year)
Source: Assumption (ASCE, 2021).
Derivation: 0.75% of $8.85B = $12.5M (within 0.5-1%).
13. Training: $3M (1 year)
Source: Assumption (AWWA, 2020 norm).
Derivation: $1M-$5M, $3M midpoint.

Heat Transfer Assumptions

Initial water temperature, T_i (oC)	4	oC	277.15	K
Thermal conductivity of the pipe material, K (W/m.K)	2	W/(m·K)		

Average temperature of the surrounding soil, T_s (K)	10	K		
Outer diameter of the pipe, D_o (m)	1.05	m		
Inner diameter of the pipe, D_i (m)	0.75	m		
Thermal conductivity of the soil, K_s (W/m·K)	1	W/(m.K)		
Outer radius of the soil influence area, R_o (m)	2.625	m		
Outer radius of the pipe, R_i (m)	0.525	m		
Convection heat transfer coefficient, h (W/m^2·K)	1000	W/m^2. K		
Volumetric flow rate, Q_f	0.88	m^3/s		
Density of water, p_w	997	kg/m^3		

Mass flow rate of water, m (kg/s)	877.36	kg/s		
Specific heat capacity of water, Cp (J/kg)	4184	J/kg		