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Water Transfer Pipeline from the Congo River to Northern Africa: Addressing Agricultural Needs and Climate Challenges

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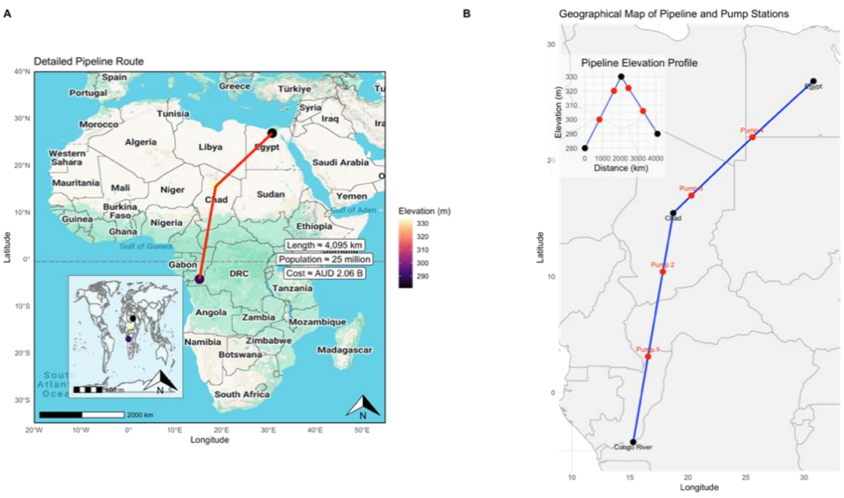
Graphical Abstract



The proposed transnational pipeline spans approximately 4,095 km, is expected to benefit 25 million people, and is estimated to cost AUD 2.06 billion.

Abstract

The uneven distribution of global water resources necessitates trans-regional water transfer to alleviate shortages. This study proposes a pipeline from the Congo River through Chad to Egypt to address water scarcity in the Nile Delta. The pipeline spans approximately 4,094 km, featuring four pumping stations equipped with Grundfos NBG 300-250-350/370 centrifugal pumps, with each station housing 22 pumps to maintain a flow rate of 432,000 m³/day. The project could help 25 million people. This design chooses to use solar energy to reduce carbon emissions by approximately 95%. The total investment is estimated at 2.06 billion Australian dollars, covering both capital and operational costs. Geospatial analysis and hydraulic modelling optimize the route, minimizing pressure loss and energy consumption. The study demonstrates feasibility with engineering adjustments and risk management.

Keywords: Transnational Water Transfer, Sustainable Water Management, Hydraulic Modelling, Geospatial Analysis, Climate Impact Assessment, Risk Management

1. Introduction

1.1 Research background

The distribution of global water resources is extremely uneven, and trans-regional water transfer has become an important means to alleviate water shortage[1,2]. Droogers et al. analyzed in North Africa, especially Egypt, water scarcity has severely limited agricultural production and economic development[3]. Egypt's main water source, the Nile, is under pressure from climate change, population growth and competition for water from upstream countries[4,5].

The study proposes to alleviate water scarcity in the Nile Delta by channelling water from the Congo River to Egypt via Chad and promoting regional cooperation and sustainable management, but the project faces significant geographical, technical, environmental and economic challenges that require a systematic feasibility study.

1.2 Challenges

The transnational water diversion project faces multiple challenges, including the need for the pipeline to adapt to the extreme environment of the tropical rainforest, the arid Sahel region and the Sahara Desert. The height difference along the route is large, so the pump station layout and pipeline slope need to be optimized to reduce energy loss[6]. Water sources need to be pre-treated, pipeline materials need to be considered for corrosion resistance, high pressure bearing capacity and wind erosion resistance, and complex geographical conditions must be addressed for construction, maintenance and laying methods[7,8].

It is necessary to analyse temperature changes along the pipeline i.e. equatorial, Sahel and desert climate conditions.

The Congo River basin is the equatorial region, which has a humid climate and abundant rainfall, but the stability of pipeline materials may be affected by high temperature and high humidity[9]. Therefore, corrosion and hydrolysis resistant materials, such as high-density polyethylene (HDPE) or stainless-steel liners, must be used to ensure long-term operation of the pipeline[10].

Chad (the Sahel region) has a dry climate and a large temperature difference between day and night, and the pipeline needs to have a good thermal expansion and cold contraction adaptability and take insulation or heat dissipation measures to reduce material fatigue caused by temperature changes. Egypt's Sahara Desert is extremely hot and UV intense, which can lead to the aging of pipeline materials, and wind erosion will aggravate the surface wear of the pipeline. Therefore, the outer layer should be coated with anti-ultraviolet coating, and design anti-sand measures, such as partially buried pipes or the use of guardrail protection[11].

The route involves a wide range of terrain from the low-lying rainforest of the Congo Basin to the semi-arid plains near Lake Chad to the highlands of the Sahara Desert. Due to terrain changes, water needs to be transported through a multi-stage booster pump station, so the layout of the pump station and energy consumption control need to be considered. How to rationally plan the spacing and head of pumping stations, reduce energy consumption and optimize transportation efficiency is a difficult point. Because the route is long and the terrain varies greatly, it may involve steep sections, which can lead to a sharp increase in pressure inside the pipeline, so pressure buffer systems such as pressure regulators and buffer reservoirs need to be designed to prevent pipeline rupture or leakage.

Because long-distance transportation involves multiple areas, some areas may have geological disasters such as mudslides, earthquakes or dune movements, and it is necessary to carry out detailed geological surveys and take adaptive measures, such as avoiding landslide-prone areas or taking protective reinforcement.

1.3 Research objectives

The main objectives of this study include:

The mathematical model of large-scale water resources transportation is constructed.

Optimize water pipeline route and hydraulic system to improve transportation efficiency.

Combined with technology, structure and economy, the comprehensive feasibility analysis is carried out.

1.4 Current Situation

At present, there are several large-scale water transfer projects for reference. First, China's South-to-North Water Transfer project has proved the technical feasibility of long-distance and large-flow water transfer[12,13]. The California State Water Project in the United States has provided experience in water transfer and reservoir management across climatic zones[14]. The Great Man-made River project in Libya demonstrates the challenges of pipeline construction and maintenance in a desert environment[15]. The Congo Enga hydropower project exemplifies the experience of large-scale infrastructure construction in the Congo region[16].

This study will draw on the technology, optimization methods and policy framework of the above engineering cases to develop a reasonable implementation plan for the Congo-Egypt water pipeline project.

2. Methods

2.1 Geospatial Analysis and Pipeline Route Selection

Geospatial analysis was employed to identify the optimal pipeline route for transnational water transport from Congo to Egypt via Chad. Elevation data were systematically extracted using the elevatr R package, and Geographic Information

Systems (GIS) analyses were conducted using the sf and ggmap R packages. Critical nodes along the pipeline route (Congo, Chad, Egypt) were defined and transformed into spatial (sf) objects to accurately determine elevation values. These spatial data points were then integrated into detailed geospatial visualizations to assess topographical constraints and optimize the pipeline route.

2.2 Hydraulic Modelling and Flow Analysis

First, the design needs to know the total length of the pipe. The length of the pipeline is initially estimated by defining the latitude and longitude of the three key points and connecting these points into a line with R.

This project is mainly aimed at solving agricultural needs and climate challenges, so a medium-sized water supply system is adopted, and the flow rate is designed to be 10 m^3/s[17,18]. Use the continuity equation to solve the pipe diameter:

$$Q = A \times v = \frac{\pi D^2}{4} \times v \quad (1)$$

Water speed choose 1.5m/s to avoid too low to cause deposition, too high to cause friction loss and noise. From this, the pipe diameter D is calculated. In this design, the pressure drop and flow rate are calculated by Darcy-Weisbach equation and Hazan-Williams equation, and the friction factor is solved by Colebroke-White iteration method.

Darcy-Weisbach equation:

$$\Delta P = f \times \frac{L}{D} \times \frac{\rho v^2}{2} \quad (2)$$

Hazen-Williams equation:

$$h_f = 10.67 \times L \times \frac{Q^{1.852}}{C^{1.852} \times D^{4.87}} \quad (3)$$

Colebrook-White iterative method:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\frac{k_S}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right. \quad (4)$$

The Reynolds number is calculated using the diameter (D) and assumed velocity to determine if the flow is turbulent. In turbulent flow, the Colebrook-White iterative formula is applied, and when the difference between the left and right sides is below the set accuracy, the obtained f value is the required one. After finding the friction loss, the pipe pressure drop is calculated using the Darcy-Weisbach equation. The pressure drop is then compared with the Hazen-Williams equation, and the results should align, confirming the calculation's reliability. Finally, the pressure drop is used to estimate the required pumping power.

Sensitivity analysis was then performed. It is assumed that the diameter of the pipe ranges from 2.5 m to 4.0 m, and the flow rate ranges from 5 m^3/s to 15 m^3/s[19], with other parameters remaining unchanged. Use R's ‘expand.grid’ to create a grid for pipe diameter (2.5 to 4.0 m) and flow rate (5 to 15 m^3/s). Then, use ‘mapply’ to calculate pressure drop and pump power for each combination. The result includes two contour plots: one for pressure drop vs. diameter and flow, and the other for pump power changes. The code automatically finds the parameter combination with the lowest pump power and displays the corresponding diameter, flow, pressure drop (bar), and pump power (MW).

The number of pumping stations is calculated according to the obtained results, assuming that each pumping station can provide 3 bars[20], the number of pumping stations n is calculated. To ensure that the pressure loss of each section is relatively uniform, the main pipe length is divided into n+1 parts, and the pumping station is set up respectively. The number of pumps in each pumping station is calculated by the total pressure drop and total flow. The parallel of the pump is used to hit the required flow rate, and the series is used to stack to a higher head. Finally, backup pumps need to be set up at each pumping station.

2.3 Cost and Energy Optimization

Linear programming (LP) is used to solve the optimal economic scheme[21]. Specifically, we use the number of pumps required to be installed at each pump station as a decision variable, and the combined cost of a single pump (including CAPEX and OPEX) as a coefficient of the objective function to minimize the total system cost. They need to meet technical constraints such as flow and head at the same time. Using R's 'lpSolve' package, we build such a mathematical model and solve the most economical configuration scheme.

In this project, the choice of financing mode is crucial to ensure the long-term sustainability and economic efficiency of the project. Therefore, a variety of financing strategies are adopted to adapt to the complexity and needs of the project.

2.4 Solar energy

To improve system sustainability and resilience, solar PV is proposed as a supplementary energy source for the pumping stations. Congo, Chad, and Egypt each receive over 1800 kWh/m²/year of solar irradiance, ensuring reliable generation. PV lifecycle emissions are as low as 24–50 g CO_2-eq/kWh[22], far below coal-based power (> 900 g CO_2-eq/kWh). Simulated energy payback times are 10.7 years (Congo), 9.3 years (Chad), and 8.5 years (Egypt). Combined with battery storage, PV systems can form microgrids to support off-grid pump operation with greater stability and lower environmental impact.

2.5 Climate Impact Analysis

Firstly, in the data preparation stage, the climate data used in this study came from the WorldClim database, which provided 12-month average temperature (°C) and precipitation (mm). The terra package of R language processed the monthly raster data for annual mean value and obtained the raster data of annual average temperature and annual total precipitation with

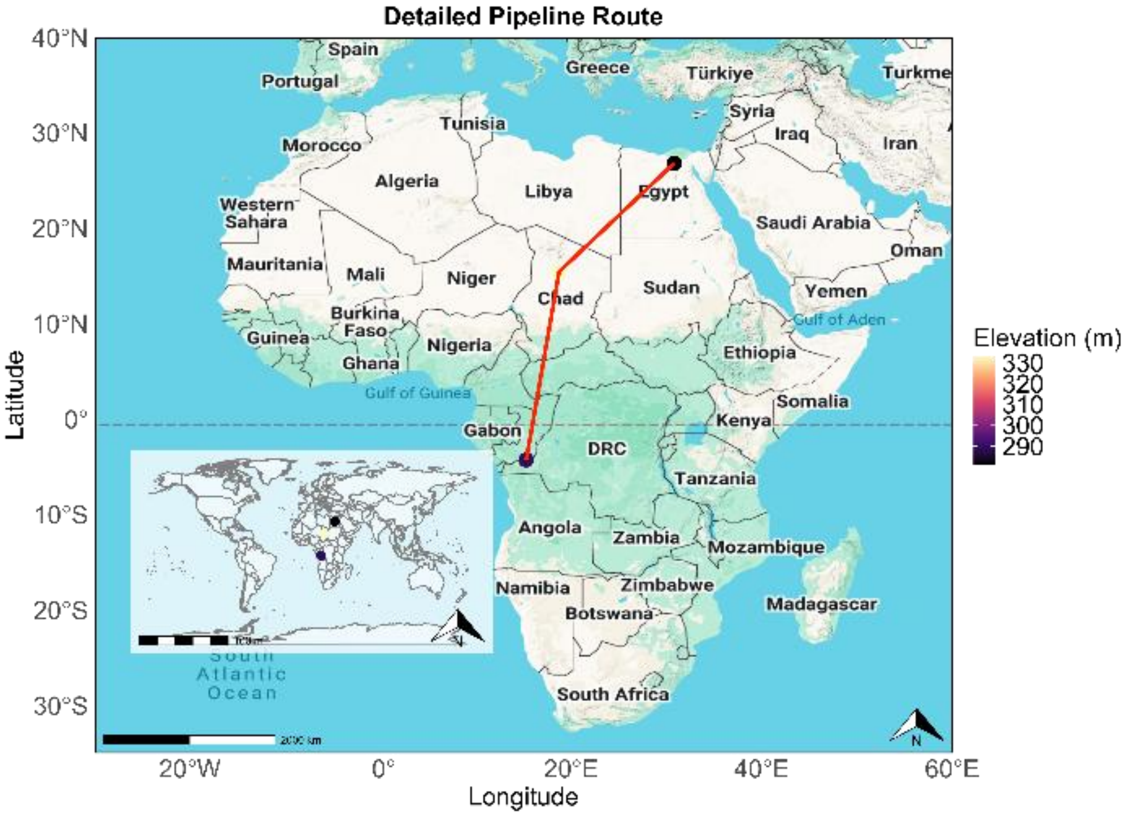


Figure 1. Optimized pipeline route from Congo via Chad to Egypt

high spatial resolution to ensure the accuracy and precision of the analysis results.

To assess possible evaporation losses along the pipeline route, an empirical estimation model based on temperature and precipitation was used:

$$E = k \times (T_{avg} - T_{min}) \times \left[1 - \frac{P_{avg}}{P_{max}}\right] \quad (5)$$

Where E represents annual evaporation (mm/year), T_{avg} and T_{min} are the average annual temperature and total annual precipitation, respectively, T_{min} and P_{max} are the empirical threshold, set at 10°C and 2000 mm, k is the empirical coefficient, with the value 0.7. The model is suitable for estimation of evaporation in arid and semi-arid regions in the absence of detailed meteorological data such as wind speed, humidity, and radiation[23,24] .

Finally, ggplot2 and viridis packages are used to superposition the pipeline path and the evaporation loss grid data, and the spatial distribution of evaporation loss is displayed in a color gradient. The results clearly reflect the variation characteristics of the intensity of evaporation loss along the pipeline, and provide an important reference for the specific design, operation and maintenance of pipeline engineering.

2.6 Risk Analysis

This design identifies the risks in the water conveyance system, including potential faults in the pipeline and pumping station. Prolonged contact with water and corrosive substances can lead to corrosion of metal parts, shortening equipment lifespan[25]. Minerals in the water may form scale, increasing friction and reducing pump efficiency[26]. Microorganisms can create biofilms, affecting flow rate and equipment operation[27]. External risks, such as device aging, external damage, and environmental factors, may also impact the system.

Risk matrixes are then used to demonstrate the severity of different risks and provide a basis for subsequent risk management. In this case, the horizontal axis represents the impact degree of the risk, from "Negligible" to "Severe"; The vertical axis shows the probability of the risk occurring, from "Very Unlikely" to "Very Likely." The risk score is obtained by multiplying the corresponding values of occurrence probability and influence degree, and the value ranges from 1 to 25. Based on the score, the risk level is divided into four levels: A score of 1-3 is Low, a score of 4-6 is Moderate, a score of 7-14 is High, and a score of 15-25 is Extreme.

3. Results and Discussion

3.1 Geospatial and Route Optimization Results

As shown in the results of Figure 1, the optimized pipeline runs from the Congo through Chad to Egypt in a variety of climatic and topographic regions, including tropical rainforests, arid grasslands, and extreme deserts. This cross-

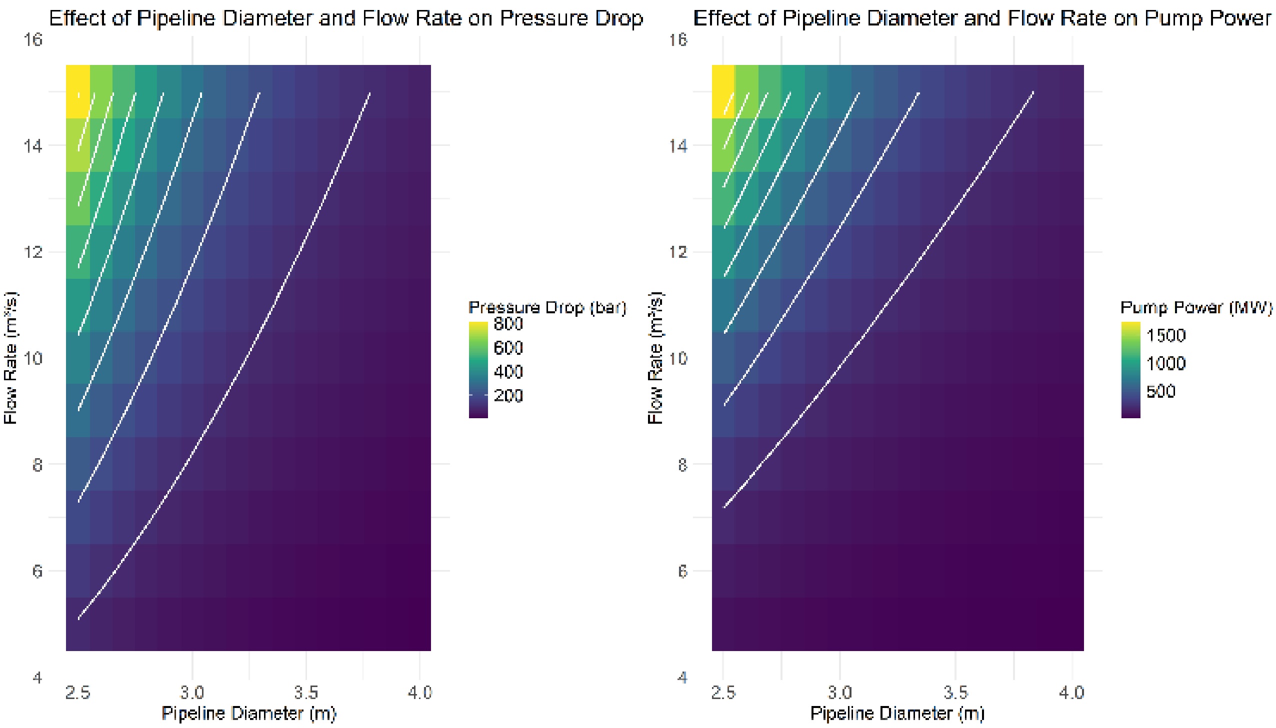


Figure 2. Pressure drop and pump power change with pipe diameter and flow rate respectively

regional design allows water to be transported from the Congo Basin, where rainfall is abundant and water resources are abundant, to the Sahel region (Chad) and the marginal Sahara region (Egypt), where water is scarce and agricultural water is stressed. The pipeline starts in the Congo at a relatively low altitude (about 290 meters), runs north through Chad (the highest altitude is about 330 meters), and ends in Egypt at an altitude of about 300 meters. It is worth noting that the transition from northern Congo to central Chad, accompanied by a gradual uplift of the terrain and a change in climate from wet to arid, requires special attention to hydraulic design (e.g. layout of pumping stations) and material selection.

3.2 Hydraulic Modelling and Pumping Station Design

A line is created from the latitude and longitude data of the key stations (Congo River, Chad, Egypt), and the total length of this line is calculated by R to be 40,946,15 meters. With a designed flow rate of 10 m^3/s and an assumed water velocity of 1.5 m/s, the diameter (D) is approximately 3 meters, based on the continuity equation. The elevation changes are as follows: the Congo River is about 280 meters above sea level (lowest point), Chad is about 330 meters above sea level (highest point), and Egypt is about 290 meters above sea level. Using the Darcy-Weisbach equation, the Hazen-Williams equation, and R code, Figure 2 is obtained.

Through these figures, it can be intuitively seen which design area has the lowest pumping energy consumption, that is, the design point of optimal energy consumption is reached.

Finally, the optimal design points are as follows: Pipeline Diameter = 4 m, Flow Rate = 5 m^3/s, Pressure Drop = 9.304492 bar, Pump Power = 6.65 MW.

The total pressure drop in the design is approximately 9.30 bar, while the system's pumping power requirement is 6.65 MW. Assuming that each pumping station is designed to provide a lift of approximately 3 bars[20], then $n \approx 4$.

Four pumping stations were initially designed on the pipeline to ensure the normal operation of the system. For the location of the pumping stations, it is assumed that the pumping stations are evenly distributed throughout the pipeline so that each station can bear a similar pressure loss. With the help of R, the distribution map of the pumping station and the corresponding elevation Figure 3 are drawn.

There are many types of pumps used in the market, such as positive displacement pumps, dynamic pumps and centrifugal pumps. The water pumped in this design is mainly used for agricultural, municipal and industrial purposes. According to the above conclusions, the flow rate is 5 m^3/s (18000 m^3/h), and the total pressure drop is about 9bar, which belongs to the condition of large flow and medium head. Centrifugal pumps are very good at handling large flows and can cover heads from a few meters to hundreds of meters[28]. Therefore, a centrifugal pump is selected in this design.

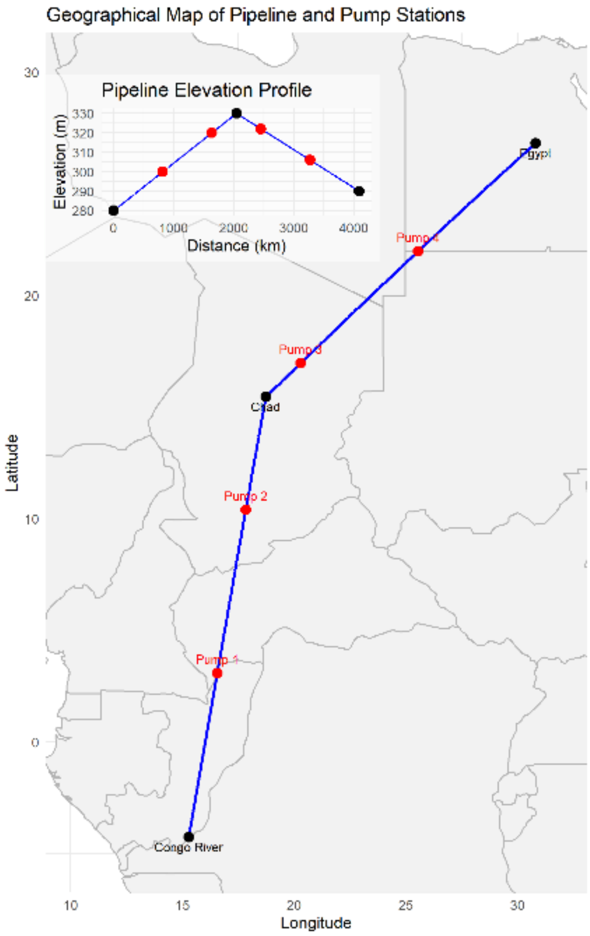


Figure 3. Distribution map of pumping station and corresponding elevation map

This design selects Grundfos NBG 300-250-350/370, whose parameters are: Rated flow: 916.5 m³/h, Rated lift: 28.86m (about 2.886 bar), Motor power: 90 kW, Speed: 1488 rpm, Price: About 63,046 AUD[29].

In this design, we required a total flow rate of 5 m³/s (i.e. 18,000 m³/h) with a total pressure drop of approximately 9.3 bar (approximately 93 m head). There are a total of 4 pumping stations, each of which distributes the total pressure drop equally, and each station bears a pressure drop of 2.325bar.

In order to achieve the total flow, it is necessary to parallel the pump, the number of parallel units is:

$$n_1 = \frac{18000}{916.5} \approx 20 \tag{7}$$

In order to achieve the total pressure drop, the pumps need to be connected in series, and only one pump in series is required in a pumping station.

Therefore, the total number of pumps required for each station is 20. Two backup pumps are placed at each pump station, so a total of 88 pumps are required.

3.3 Cost and Energy Optimization Results

To achieve the optimization of the system cost and energy consumption, a linear programming approach is used to solve the pumping station configuration scheme. The total system flow requirement is 5 m³/s (18,000 m³/h) as well as the rated flow of a single pump of 916.5 m³/h. Use this to establish flow constraints for each pump station. Number of pumps installed per pumping station: $x_i \times 916.5 \geq 18000$.

The minimum number of pumps per station is 20. This study considers both capital expenditure (CAPEX) and operating expenditure (OPEX) to evaluate long-term investment and maintenance costs. CAPEX includes the cost of purchasing and installing pumps, while OPEX covers operation, maintenance, repair, and energy use. Since CAPEX is a one-time cost, it is generally higher than OPEX. High-performance, energy-efficient centrifugal pumps are chosen despite their higher initial cost, as they offer better efficiency and a longer lifespan, ultimately reducing operating costs[30]. Table 1 shows the estimated data for each major cost item in a single pumping station. The total investment of this project is USD 1.34 billion, which is approximately 59%, or 0.59 times, the cost of Saudi Arabia’s independent water transmission pipeline project (USD 2.26 billion)[31].

Table 1. Cost estimation (CAPEX of Pumps, piping material and install, OPEX of maintenance and energy consumption)

Cost items		Detailed description	Unit price (AUD)	Quantity	Total price (AUD)
CAPEX	Pumps	Purchase of centrifugal pump	63,046[29]	88	5,550,000
	Piping material	HDPE and stainless-steel pipes. The cost of other materials	HDPE:75/m Steel:200/m	4094615m	563,000,000
	Install	Install pipes and related equipment	350/m	4094615m	1,434,000,000
OPEX	Maintenance	Maintenance costs for pipework and pumping units	3% of the total cost of pipeline construction	/	60,050,000
	Energy consumption	Energy requirements for pumps	6.65 MW/h 0.25/kWh	8760h	14,500
Total (AUD)					2,062,000,000

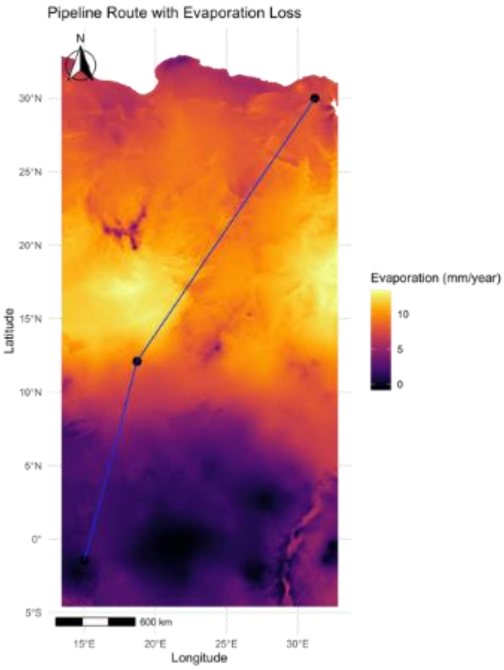


Figure 4. Spatial Distribution of Estimated Annual

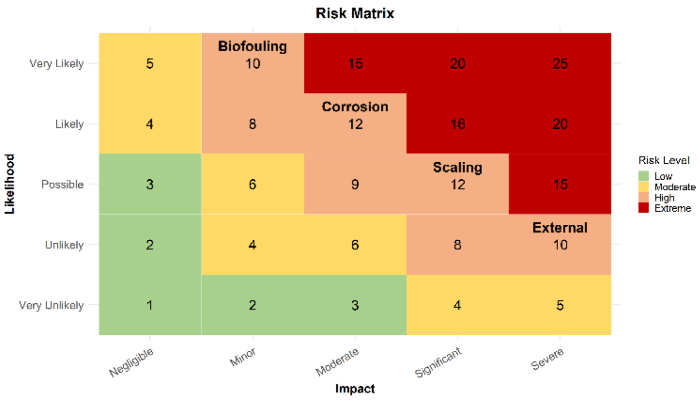


Figure 5. Risk Matrix

The project needs financial support from the government. The participation of the government brings a stable source of funding for the project and improves the protection of public interest[32]. Second, the public-private partnership (PPP) helps to spread risk, and through private investment increased financial resources, make the project more advanced and reliable in technology and operation[33]. To ensure economic independence during the operational phase, the project adopted a usage-based billing system. This promotes the rational use of water resources and provides a stable source of income for the ongoing operation of the project.

3.4 Solar PV System Cost Estimation

To reduce operational energy costs, each pump station is designed to incorporate a solar PV system sized according to local solar availability. Using 450 W panels and an 80% system efficiency, the estimated requirements are approximately 24,630 panels in Congo, 21,390 in Chad, and 18,472 in Egypt. At a unit cost of 208.94 dollars[34], the corresponding panel procurement costs are AUD 5.15 million, 4.47 million, and 3.86 million, respectively. These figures support the feasibility of integrating solar farms to improve energy autonomy and sustainability across the pipeline system.

Calculation results show that the pump station power 6.65 MW daily operation for 24 hours, the use of coal annual emissions of 52,428.6 tons of CO_2-eq, while the annual emission of solar energy 1398.1-2912.7 tons of CO_2-eq, saving carbon emissions 94.4%-97.3%.

3.5 Climate Impact

The spatial distribution of evaporation losses along the proposed transnational pipeline was assessed using climate data and previously described empirical evaporation models. The resulting map (Figure 4) shows the annual evaporation intensity of the pipeline from the Congo via Chad to Egypt (in mm/year). It can be seen from the figure that there is a significant spatial gradient in evaporation losses along the proposed pipeline route. In the southern part of the pipeline, particularly in Congo, the annual evaporation remains relatively modest, with values generally below 5 mm/year. As the pipeline extends north into Chad and Sudan, evaporation intensity increases gradually. However, even in the northernmost parts of Egypt, the simulated annual evaporation remains below 12 mm/year.

This result contradicts earlier assumptions that evaporation in the extremely arid Sahara region could exceed 2000 mm/year. The lower simulated values suggest that actual climate-driven water losses, constrained by mean temperature and annual precipitation, may be milder than initially expected.

Although the simulated evaporation rate is relatively low, the cumulative impact on more than 3,000 km of pipeline remains an important engineering consideration. Measures such as buried underground pipes, anti-evaporation materials or night-time pumping plans may further reduce losses and improve long-term operational efficiency. In addition, the model highlights the importance of using spatially explicit data rather than broad assumptions when conducting climate impact assessments on large water infrastructure. 3.6 Failure Risk

For the risk matrix (Figure 5) mentioned above:

Corrosion events, with a risk score of 16, fall in the Extreme zone, indicating high likelihood and significant impact. Prevention and maintenance should be prioritized[25].

Scaling events fall in the High category with a risk score of 9, indicating a moderate probability and impact. They can be managed through regular cleaning and water quality pretreatment[35].

Bioblockages have a moderate risk score of 6, indicating a low risk. While the risk is minor, it can be reduced through regular monitoring and cleaning[36,37].

External risk, with a risk score of 10, falls in the High zone. Key equipment should be regularly tested and updated to prevent aging[38]. Security measures and an emergency plan should also be strengthened, with real-time monitoring of weather and environmental changes to adjust operations and minimize the impact of natural disasters or extreme weather.

4. Conclusion

The water transfer pipeline project from the Congo River to North Africa is technically feasible and can effectively alleviate the water shortage problem in the target area. However, project implementation requires consideration of multiple engineering trade-offs, including environmental and water quality concerns, energy and power requirements, and engineering safety and financial risks.

Specifically, environmental and water quality issues need to be addressed through the selection of suitable materials and filtration technologies to protect water quality and reduce environmental impact. Energy efficiency can be improved by integrating renewable energy systems, thereby reducing dependence on traditional energy sources. Engineering safety needs to be ensured through precise material selection and construction techniques to prevent structural risks and maintenance failures. Finally, for long-term investment and operating costs, continuous financial planning and cost management strategies are recommended. Future work should focus on improving the durability and corrosion resistance of pipeline materials, as well as developing more efficient pumps and power systems to improve the economy and reliability of the entire water delivery system.

5. Acknowledgements

The authors of this study acknowledge that AI is used to design and modify R code and plays a key role in subsequent data visualisation.

6. Author contributions

Jingyi Yao was responsible for writing 2.2, 2.3 and 2.6 sections in the Methods. In the Results and Discussion section, Jingyi Yao wrote 3.2, 3.3, and 3.6 sections. Jingyi Yao also crafted the Conclusion section and undertook the formatting adjustments for the manuscript. At the same time, the R code corresponding to figure 2, 3, and 5 was also completed by her.

Xin Chen was responsible for writing the 2.1 and 2.5 sections in the Methods. In the "Results and Discussion" section, Xin Chen contributed to 3.1 and 3.5. Xin Chen was also responsible for developing the corresponding R code for both the geospatial and climate impact analyses.

Ruoheng Wang completed the Introduction of the section 1.1, 1.2, 1.3, 1.4, 2.4 and 3.4. She also completed the modification of the Abstract and provided suggestions for the subsequent pipeline establishment

Dr. Gobinath Rajarathnam provided conceptual guidance and project supervision, ensuring the research direction and quality adhered to academic standard.

References

[1] Han, M., Chen, G. & Li, Y. Global water transfers embodied in international trade: Tracking imbalanced and inefficient flows. *Journal of cleaner production* **184**, 50-64 (2018).

[2] Kazumba, S., Gillerman, L. & Oron, G. Managing Trans-Regional Water Transfer in Dry African Countries to Mitigate Shortages. *Journal of Innovative Research in Engineering and Sciences* **2**, 249-273 (2011).

[3] Droogers, P. *et al.* Water resources trends in Middle East and North Africa towards 2050. *Hydrology and Earth System Sciences* **16**, 3101-3114 (2012).

[4] Ashour, M., El Attar, S., Rafaat, Y. & Mohamed, M. Water resources management in Egypt. *JES. Journal of Engineering Sciences* **37**, 269-279 (2009).

[5] Abd El Moniem, A. A. Overview of water resources and requirements in Egypt; the factors controlling its management and development. *Journal of Environmental Studies* **2**, 82-97 (2009).

[6] Gong, Y. & Cheng, J. Optimization of cascade pumping stations' operations based on head decomposition–dynamic programming aggregation method considering water level requirements. *Journal of Water Resources Planning and Management* **144**, 04018034 (2018).

[7] Skretas, A., Gyftakis, S. & Marcoulaki, E. A demonstration of sustainable pipeline routing optimization using detailed financial and environmental assessment. *Journal of Cleaner Production* **362**, 132305 (2022).

[8] Almheiri, Z., Meguid, M. & Zayed, T. Review of Critical Factors Affecting the Failure of Water Pipeline Infrastructure. *Journal of Water Resources Planning and Management* **149**, 03123001 (2023).

[9] Toulmin, C. *Climate change in Africa*. (Bloomsbury Publishing, 2009).

[10] Nguyen, K. Q. *et al.* Long-term testing methods for HDPE pipe-advantages and disadvantages: A review. *Engineering Fracture Mechanics* **246**, 107629 (2021).

[11] Condini, A. UV-CURABLE PROTECTIVE COATING FOR THE INNER SURFACE OF STEEL PIPES. (2024).

[12] Zhao, Z.-Y., Zuo, J. & Zillante, G. Transformation of water resource management: a case study of the South-to-North Water Diversion project. *Journal of cleaner production* **163**, 136-145 (2017).

[13]Tang, C., Yi, Y., Yang, Z. & Cheng, X. Water pollution risk simulation and prediction in the main canal of the South-to-North Water Transfer Project. *Journal of Hydrology* **519**, 2111-2120 (2014).
[14]Chung, I. & Helweg, O. Modeling the California state water project. *Journal of Water Resources Planning and Management* **111**, 82-97 (1985).
[15]Kuwairi, A. in *Proceedings of the Institution of Civil Engineers-Civil Engineering.* 39-43 (Thomas Telford Ltd).
[16]Oyewo, A. S., Farfan, J., Peltoniemi, P. & Breyer, C. Repercussion of large scale hydro dam deployment: the case of Congo Grand Inga hydro project. *Energies* **11**, 972 (2018).
[17]Mays, L. W. *Water resources engineering*. (John Wiley & Sons, 2010).
[18]Nitivattananon, V., Sadowski, E. C. & Quimpo, R. G. Optimization of water supply system operation. *Journal of water resources planning and management* **122**, 374-384 (1996).
[19]Stephenson, D. *Pipeline design for water engineers*. Vol. 40 (Elsevier, 1989).
[20]Menon, E. S. *Working Guide to Pump and Pumping Stations: Calculations and Simulations*. (Gulf Professional Publishing, 2009).
[21]Vaccari, M., Mancuso, G., Riccardi, J., Cantù, M. & Pannocchia, G. A sequential linear programming algorithm for economic optimization of hybrid renewable energy systems. *Journal of process control* **74**, 189-201 (2019).
[22]Fthenakis, V. M., Kim, H. C. & Alsema, E. Emissions from photovoltaic life cycles. *Environmental science & technology* **42**, 2168-2174 (2008).
[23]Xiong, Y. J., Zhao, W. L., Wang, P., Paw U, K. T. & Qiu, G. Y. Simple and applicable method for estimating evapotranspiration and its components in arid regions. *Journal of Geophysical Research: Atmospheres* **124**, 9963-9982 (2019).
[24]Awal, R., Habibi, H., Fares, A. & Deb, S. Estimating reference crop evapotranspiration under limited climate data in West Texas. *Journal of Hydrology: Regional Studies* **28**, 100677 (2020).
[25]Hussein Farh, H. M., Ben Seghier, M. E. A., Taiwo, R. & Zayed, T. Analysis and ranking of corrosion causes for water pipelines: A critical review. *NPJ Clean Water* **6**, 65 (2023).
[26]Kazi, S., Duffy, G. & Chen, X. Mineral scale formation and mitigation on metals and a polymeric heat exchanger surface. *Applied Thermal Engineering* **30**, 2236-2242 (2010).
[27]Vishwakarma, V. Impact of environmental biofilms: Industrial components and its remediation. *Journal of basic microbiology* **60**, 198-206 (2020).
[28]Karassik, I. & McGuire, J. T. *Centrifugal pumps*. (Springer Science & Business Media, 2012).
[29]Grundfos. *NBG 300-250-350/370 technical specifications*, < https://product-selection.grundfos.com/au/products/nbg-nbge/nbg/nbg-300-250-350370-98307051?pumpsystemid=2625522505&tab=variant-specifications> (
[30]Kaya, D., Çanka Kılıç, F. & Öztürk, H. H. in *Energy Management and Energy Efficiency in Industry: Practical Examples* 329-374 (Springer, 2021).
[31]World, I. *Agreements signed for US$22.6 billion independent water transmission pipeline in Saudi Arabia*, <https://www.infrapppworld.com/news/agreements-signed-for-us226-billion-independent-water-transmission-pipeline-in-saudi-arabia> (
[32]Anderson, M. B., Petrie, M., Alier, M. M., Cangiano, M. M. & Hemming, M. R. *Public-private partnerships, government guarantees, and fiscal risk*. (International Monetary Fund, 2006).
[33]Grimsey, D. & Lewis, M. K. in *Public Private Partnerships* (Edward Elgar Publishing, 2004).
[34]SolarOnline. *Solar Online Australia*, <https://solaronline.com.au/solar-panels.html?srsltid=AfmBOoqW_orA8GK32qazMwM1-qUj5MJKzmd-_egge_PacruN6EVsfS9d> (
[35]Sutzkover-Gutman, I. & Hasson, D. Feed water pretreatment for desalination plants. *Desalination* **264**, 289-296 (2010).
[36]Flemming, H.-C. Microbial biofouling: unsolved problems, insufficient approaches, and possible solutions. *Biofilm highlights*, 81-109 (2011).
[37]Shi, X., Tal, G., Hankins, N. P. & Gitis, V. Fouling and cleaning of ultrafiltration membranes: A review. *Journal of Water Process Engineering* **1**, 121-138 (2014).
[38]Kraak, D. *et al.* in *2018 IEEE 23rd European Test Symposium (ETS).* 1-10 (IEEE).

Supplementary

R code of Figure 1:

```
 # ===== Install and load required R packages (if not already installed) =====
packages <- c("ggplot2", "ggmap", "sf", "elevatr", "ggspatial", "dplyr", "gridExtra")
new_packages <- packages[!(packages %in% installed.packages()[,"Package"])]
if(length(new_packages)) install.packages(new_packages)

library(ggplot2)
library(ggmap)
library(sf)
library(elevatr)
library(ggspatial)
library(dplyr)
library(gridExtra)
library(cowplot)

# ===== Set your Google API Key (replace with your actual API Key) =====
register_google(key = "AIzaSyB__tXcP0Rp5XwCw8MfRcxDhkVZiJuZQ7U")  # Replace with your API Key

# 1. Define pipeline stations (Congo → Chad → Egypt)
locations <- data.frame(
  name = c("Congo River", "Chad", "Egypt"),
  lat = c(-4.267, 15.4542, 26.8206),
  lon = c(15.283, 18.7322, 30.8025)
)

# 2. Convert to sf object
locations_sf <- st_as_sf(locations, coords = c("lon", "lat"), crs = 4326)

# 3. Retrieve DEM (elevation) data
elev_data <- get_elev_point(locations_sf, prj = st_crs(4326), src = "aws")
locations_sf$elevation <- elev_data$elevation  # Add elevation info

# 4. Create pipeline line (connect stations)
pipeline_line <- st_sfc(st_linestring(as.matrix(locations[, c("lon", "lat")])), crs = 4326)
pipeline_sf <- st_sf(geometry = pipeline_line)

# 5. Retrieve basemap
bbox_africa <- c(left = -20, bottom = -35, right = 55, top = 40)
map_base_africa <- get_googlemap(center = c(lon = 17.5, lat = 2.5), zoom = 3, maptype = "terrain")

# 6. Plot global pipeline map
region_map <- ggmap(map_base_africa) +
  geom_sf(data = locations_sf, aes(color = elevation), size = 5, inherit.aes = FALSE) +
  geom_sf(data = pipeline_sf, color = "red", linewidth = 1.5, inherit.aes = FALSE) +
  scale_color_viridis_c(option = "magma", name = "Elevation (m)", guide = guide_colorbar(position = "right")) +
  coord_sf(xlim = c(-20, 55), ylim = c(-35, 40), expand = FALSE) +
  labs(title = "Detailed Pipeline Route", x = "Longitude", y = "Latitude") +
  annotation_scale(location = "bl", width_hint = 0.3) +
  annotation_north_arrow(location = "br", which_north = "true", height = unit(1, "cm")) +
  theme_minimal() +
  theme(
```

```
    legend.position = c(0.85, 0.2),
    panel.border = element_rect(color = "black", linewidth = 1, fill = NA))

# 7. Plot elevation inset map

# Ensure `locations` includes elevation data
locations$elevation <- elev_data$elevation

# Use the data frame `locations` instead of `locations_sf`
world_map <- ggplot() +
  borders("world", colour = "gray50", fill = "white", alpha = 0.5) +  # 50% transparent background
  geom_point(data = locations, aes(x = lon, y = lat, color = elevation), size = 3) +
  scale_color_viridis_c(option = "magma", name = "Elevation (m)", guide = "none") +  # Remove legend for inset
  theme_void() +
  annotation_scale(location = "bl", width_hint = 0.3) +
  annotation_north_arrow(location = "br", which_north = "true", height = unit(1, "cm")) +
  theme(
    legend.position = "none",  # Hide legend in inset
    panel.background = element_rect(fill = alpha("white", 0.5), color = "black"),  # 50% transparent background
    plot.background = element_rect(fill = alpha("white", 0.5), color = "black")  # Maintain border visibility
  )

# 8. Combine map and elevation inset
final_plot <- ggdraw() +
  draw_plot(region_map, x = 0, y = 0, width = 1, height = 1) +
  draw_plot(world_map, x = 0.15, y = 0.2, width = 0.25, height = 0.25)  # Adjust inset placement

# 9. Display the final plot
print(final_plot)

# ====== Save to PNG with 10:10 ratio ======
ggsave("combined_pipeline_plot_16x9.png", plot = final_plot, width = 10, height = 10, dpi = 400)
```

R code of Figure 2:

```
# Install and load required packages
if (!require(ggplot2)) install.packages("ggplot2")
if (!require(gridExtra)) install.packages("gridExtra")
if (!require(viridis)) install.packages("viridis")
library(ggplot2)
library(gridExtra)
library(viridis)

# ======= Fixed Parameters =======
L    <- 4094615      # Total pipeline length in meters
ks   <- 0.0001       # Pipe roughness in meters
nu   <- 1.007e-6     # Kinematic viscosity of water in m²/s
rho  <- 1000         # Density of water in kg/m³
g    <- 9.81         # Gravitational acceleration in m/s²
efficiency <- 0.7    # Pump efficiency (dimensionless)

# ======= Colebrook-White Iterative Function =======
colebrook <- function(Re, ks, D, tol = 1e-6, max_iter = 100) {
  f <- 0.02  # Initial guess for friction factor
```

```
  for (i in 1:max_iter) {
    lhs <- 1 / sqrt(f)
    rhs <- -2 * log10((ks / (3.7 * D)) + (2.51 / (Re * sqrt(f))))
    if (abs(lhs - rhs) < tol) break
    f <- 1 / (rhs^2)
  }
  return(f)
}

# ======= Function to Calculate Pressure Drop =======
calc_pressure_drop <- function(D, Q) {
  A <- pi * (D / 2)^2                # Cross-sectional area in m²
  v <- Q / A                         # Average flow velocity in m/s
  Re <- (v * D) / nu                 # Reynolds number
  f <- colebrook(Re, ks, D)          # Friction factor
  deltaP <- f * (L / D) * (rho * v^2 / 2)  # Pressure drop in Pascals
  return(deltaP)
}

# ======= Function to Calculate Pump Power =======
calc_pump_power <- function(D, Q) {
  deltaP <- calc_pressure_drop(D, Q)
  pump_power <- Q * deltaP / efficiency  # Pump power in Watts
  return(pump_power)
}

# ======= Sensitivity Analysis =======
D_values <- seq(2.5, 4.0, by = 0.1)       # Pipeline diameters (m)
Q_values <- seq(5, 15, by = 1)            # Flow rates (m³/s)
param_grid <- expand.grid(D = D_values, Q = Q_values)

param_grid$PressureDrop <- mapply(calc_pressure_drop, param_grid$D, param_grid$Q)
param_grid$PumpPower <- mapply(calc_pump_power, param_grid$D, param_grid$Q)

# Convert to more readable units
param_grid$PumpPower_MW <- param_grid$PumpPower / 1e6         # MW
param_grid$PressureDrop_bar <- param_grid$PressureDrop / 1e5  # bar

# ======= Plot: Pressure Drop =======
p1 <- ggplot(param_grid, aes(x = D, y = Q, z = PressureDrop_bar)) +
  geom_tile(aes(fill = PressureDrop_bar)) +
  geom_contour(color = "white", size = 0.8) +
  scale_fill_viridis_c(name = "Pressure Drop (bar)") +
  labs(title = "Effect of Pipeline Diameter and Flow Rate on Pressure Drop",
       x = "Pipeline Diameter (m)",
       y = "Flow Rate (m³/s)") +
  theme_minimal()

# ======= Plot: Pump Power =======
p2 <- ggplot(param_grid, aes(x = D, y = Q, z = PumpPower_MW)) +
  geom_tile(aes(fill = PumpPower_MW)) +
  geom_contour(color = "white", size = 0.8) +
  scale_fill_viridis_c(name = "Pump Power (MW)") +
```

```
  labs(title = "Effect of Pipeline Diameter and Flow Rate on Pump Power",
       x = "Pipeline Diameter (m)",
       y = "Flow Rate (m³/s)") +
  theme_minimal()

# ======= Show Both Plots One Above the Other =======
final_combined_plot <- grid.arrange(p1, p2, ncol = 2)

# ======= Save to PNG with 16:9 ratio =======
ggsave("combined_pipeline_plots_16x9.png", plot = final_combined_plot, width = 16, height = 9, dpi = 300)

# ======= Find Optimal Design (Minimum Pump Power) =======
min_idx <- which.min(param_grid$PumpPower_MW)
optimal <- param_grid[min_idx, ]
cat("Optimal Design:\n")
cat("Pipeline Diameter =", optimal$D, "m\n")
cat("Flow Rate =", optimal$Q, "m³/s\n")
cat("Pressure Drop =", optimal$PressureDrop_bar, "bar\n")
cat("Pump Power =", optimal$PumpPower_MW, "MW\n")
```

R code of Figure 3:

```
# ====== Ensure Required Packages Are Installed ======
required_packages <- c("sf", "ggplot2", "cowplot", "maps")

for (pkg in required_packages) {
  if (!require(pkg, character.only = TRUE)) {
    install.packages(pkg)
    library(pkg, character.only = TRUE)
  }
}

library(sf)
library(ggplot2)
library(cowplot)
library(maps)

# ------------------- 1. Define Key Locations and Create Pipeline Line -------------------
locations <- data.frame(
  name = c("Congo River", "Chad", "Egypt"),
  lon  = c(15.283, 18.7322, 30.8025),
  lat  = c(-4.267, 15.4542, 26.8206)
)

locations_sf <- st_as_sf(locations, coords = c("lon", "lat"), crs = 4326)
pipeline_line <- st_sfc(st_linestring(as.matrix(locations[, c("lon", "lat")])), crs = 4326)

# ------------------- 2. Example Elevation Profile Data -------------------
L_total <- 4094615  # Total pipeline length in meters
dist_seq <- seq(0, L_total, length.out = 1000)
control_dist <- c(0, L_total/2, L_total)
control_elev <- c(280, 330, 290)
elev_profile <- approx(x = control_dist, y = control_elev, xout = dist_seq)$y
```

```
elev_df <- data.frame(
  Distance_km = dist_seq / 1000,
  Elevation_m = elev_profile
)

# Key locations on the elevation profile (marked in black)
locations_elev <- data.frame(
  name = c("Congo River", "Chad", "Egypt"),
  Distance_km = c(0, (L_total/2)/1000, L_total/1000),
  Elevation_m = c(280, 330, 290)
)

# ------------------- 3. Determine Pump Station Positions on the Elevation Profile -------------------
# Assume 4 pump stations located at 1/5, 2/5, 3/5, 4/5 of the pipeline length
pump_station_fraction <- c(1/5, 2/5, 3/5, 4/5)
pump_station_dist <- pump_station_fraction * L_total
pump_station_elev <- approx(x = dist_seq, y = elev_profile, xout = pump_station_dist)$y

pump_elev_df <- data.frame(
  Distance_km = pump_station_dist / 1000,
  Elevation_m = pump_station_elev,
  station     = paste("Pump", 1:length(pump_station_elev))
)

# ------------------- 4. Create the Elevation Profile Plot (p_elev) -------------------
p_elev <- ggplot(elev_df, aes(x = Distance_km, y = Elevation_m)) +
  geom_line(color = "blue") +
  # Key locations (black points)
  geom_point(data = locations_elev, aes(x = Distance_km, y = Elevation_m),
             color = "black", size = 3) +
  # Pump stations (red points)
  geom_point(data = pump_elev_df, aes(x = Distance_km, y = Elevation_m),
             color = "red", size = 3) +
  labs(title = "Pipeline Elevation Profile",
       x = "Distance (km)", y = "Elevation (m)") +
  theme_minimal() +
  # Set background to white with 50% transparency
  theme(
    plot.background  = element_rect(fill = alpha("white", 0.5), color = NA),
    panel.background = element_rect(fill = alpha("white", 0.5), color = NA)
  )

# ------------------- 5. Prepare Map Data: Pipeline and Pump Stations -------------------
world_map <- map_data("world")

# Sample pipeline points for the route (blue line)
pipeline_line_proj <- st_transform(pipeline_line, 3857)
pipeline_points_proj <- st_line_sample(pipeline_line_proj, sample = seq(0, 1, length.out = 1000))
pipeline_points <- st_transform(pipeline_points_proj, 4326)
pipeline_coords <- st_coordinates(pipeline_points)
pipeline_df <- data.frame(pipeline_coords)
names(pipeline_df) <- c("lon", "lat")
```

```
# Example pump stations on the geographic map
pump_stations_proj <- st_line_sample(pipeline_line_proj, sample = pump_station_fraction)
pump_stations <- st_transform(pump_stations_proj, 4326)
pump_stations_coords <- st_coordinates(pump_stations)
pump_stations_df <- data.frame(
  lon = pump_stations_coords[,1],
  lat = pump_stations_coords[,2],
  station = paste("Pump", 1:nrow(pump_stations_coords))
)

# ------------------- 6. Create the Geographical Map Plot (p_map) -------------------
xlim_vals <- c(10, 32)
ylim_vals <- c(-5, 30)

p_map <- ggplot() +
  geom_polygon(data = world_map, aes(x = long, y = lat, group = group),
               fill = "gray95", color = "gray70") +
  geom_path(data = pipeline_df, aes(x = lon, y = lat),
            color = "blue", size = 1) +
  geom_point(data = pump_stations_df, aes(x = lon, y = lat),
             color = "red", size = 3) +
  geom_text(data = pump_stations_df, aes(x = lon, y = lat, label = station),
            color = "red", vjust = -1, size = 3) +
  geom_point(data = locations, aes(x = lon, y = lat),
             color = "black", size = 3) +
  geom_text(data = locations, aes(x = lon, y = lat, label = name),
            color = "black", vjust = 1.5, size = 3) +
  coord_fixed(ratio = 1, xlim = xlim_vals, ylim = ylim_vals) +
  labs(title = "Geographical Map of Pipeline and Pump Stations",
       x = "Longitude", y = "Latitude") +
  theme_minimal()

# ------------------- 7. Combine the Plots: Embed p_elev into p_map -------------------
final_plot <- ggdraw() +
  draw_plot(p_map, x = 0, y = 0, width = 1, height = 1) +
  # Embed the elevation plot at the left-top corner (adjust x, y, width, height as needed)
  draw_plot(p_elev, x = 0.2, y = 0.65, width = 0.25, height = 0.25)

# Display the final combined plot
print(final_plot)

# ------------------- 7. Combine the Plots: Embed p_elev into p_map -------------------
final_plot <- ggdraw() +
  draw_plot(p_map, x = 0, y = 0, width = 1, height = 1) +
  draw_plot(p_elev, x = 0.35, y = 0.72, width = 0.2, height = 0.2)

# Display the final combined plot
print(final_plot)

# ====== Save to PNG with 16:9 ratio ======
ggsave("combined_pipeline_plot_16x9.png", plot = final_plot, width = 16, height = 9, dpi = 300)
```

R code of Figure 4:

```
# ===== 1. Install and load all required packages =====
install.packages(c("terra", "sf", "ggplot2", "ggspatial", "viridis", "rnaturalearth", "rnaturalearthdata"))

library(terra)          # For handling raster data
library(sf)             # For handling spatial vector data
library(ggplot2)        # Core plotting package
library(ggspatial)      # For scale bar and north arrow
library(viridis)        # High-quality color scales
library(rnaturalearth)  # Optional background geographic data
library(rnaturalearthdata)

# ===== 2. Set your data directory path =====
downloads_path <- "~/Downloads/"  #  Modify based on your actual file path

# ===== 3. Load temperature and precipitation raster data ( please change filepath to your computer specifically
) =====
temp_files <- sort(list.files(path = downloads_path, pattern = "wc2.1_30s_tavg_.*\\.tif$", full.names = TRUE))
precip_files <- sort(list.files(path = downloads_path, pattern = "wc2.1_30s_prec_.*\\.tif$", full.names = TRUE))

# Read raster stacks
temp_raster <- rast(temp_files)
precip_raster <- rast(precip_files)

# ===== 4. Calculate annual mean temperature and total precipitation =====
avg_temp_raster <- mean(temp_raster)            # °C
total_precip_raster <- sum(precip_raster)       # mm/year

# ===== 5. Evaporation loss estimation model =====
k <- 0.7
T_min <- 10
P_max <- 2000

evap_raster <- k * (avg_temp_raster - T_min) * (1 - (total_precip_raster / P_max))

# ===== 6. Define pipeline stations (Congo → Chad → Egypt) =====
pipeline_stations <- data.frame(
  station = c("Congo", "Chad", "Egypt"),
  lat = c(-1.45, 12.1, 30.0),
  lon = c(15.0, 18.7, 31.2)
)

pipeline_sf <- st_as_sf(pipeline_stations, coords = c("lon", "lat"), crs = 4326)
pipeline_route <- st_linestring(matrix(unlist(pipeline_stations[, c("lon", "lat")]), ncol = 2, byrow = FALSE))
pipeline_route_sf <- st_sfc(pipeline_route, crs = 4326)

# ===== 7. Expand bounding box and crop evaporation raster =====
pipeline_bbox <- st_bbox(pipeline_sf)
expand_factor <- 0.1
x_range <- (pipeline_bbox$xmax - pipeline_bbox$xmin) * expand_factor
y_range <- (pipeline_bbox$ymax - pipeline_bbox$ymin) * expand_factor

expanded_bbox <- terra::ext(
  pipeline_bbox$xmin - x_range,
```

```
  pipeline_bbox$xmax + x_range,
  pipeline_bbox$ymin - y_range,
  pipeline_bbox$ymax + y_range
)

evap_raster_expanded <- crop(evap_raster, expanded_bbox)

# ===== 8. Convert raster to dataframe for ggplot2 visualization =====
evap_df_expanded <- as.data.frame(evap_raster_expanded, xy = TRUE)
colnames(evap_df_expanded)[3] <- "evap"  # Rename column for ggplot fill aesthetic

# ===== 9. Create evaporation loss map with pipeline overlay =====
ggplot() +
  geom_raster(data = evap_df_expanded, aes(x = x, y = y, fill = evap)) +
  scale_fill_viridis(name = "Evaporation (mm/year)", option = "inferno") +
  geom_sf(data = pipeline_sf, color = "black", size = 3) +
  geom_sf(data = pipeline_route_sf, color = "blue", size = 1.2) +
  annotation_scale(location = "bl", width_hint = 0.3) +
  annotation_north_arrow(location = "tl", which_north = "true",
                         style = north_arrow_fancy_orienteering) +
  labs(title = "Pipeline Route with Evaporation Loss",
       x = "Longitude", y = "Latitude") +
  theme_minimal()

# ====== Save evaporation map to PNG with 10:8 ratio ======
ggsave("pipeline_evaporation_map_.png",
       width = 10, height = 8, dpi = 400)
```

R code of Figure 5:

```
# ====== Install and Load Required Package ======
if (!require(ggplot2)) install.packages("ggplot2")
library(ggplot2)

# ====== Create the Base Risk Matrix ======
risk_matrix <- expand.grid(
  Likelihood = factor(c("Very Unlikely", "Unlikely", "Possible", "Likely", "Very Likely"),
                      levels = c("Very Unlikely", "Unlikely", "Possible", "Likely", "Very Likely")),
  Impact = factor(c("Negligible", "Minor", "Moderate", "Significant", "Severe"),
                  levels = c("Negligible", "Minor", "Moderate", "Significant", "Severe"))
)

# ====== Calculate Risk Scores ======
risk_matrix$Score <- as.numeric(risk_matrix$Likelihood) * as.numeric(risk_matrix$Impact)

# ====== Define Risk Levels ======
risk_matrix$RiskLevel <- cut(risk_matrix$Score,
                             breaks = c(0, 3, 6, 14, 25),
                             labels = c("Low", "Moderate", "High", "Extreme"))

# ====== Color Scheme for Risk Levels ======
risk_colors <- c("Low" = "#A8D08D",       # green
                 "Moderate" = "#FFD966",  # yellow
                 "High" = "#F4B084",      # orange
```

```
                "Extreme" = "#C00000")   # red

  # ====== Define Risk Events and Positions ======
  events <- data.frame(
    Event = c("Corrosion", "Scaling", "Biofouling", "External"),
    Likelihood = factor(c("Likely", "Possible", "Very Likely", "Unlikely"),
                        levels = c("Very Unlikely", "Unlikely", "Possible", "Likely", "Very Likely")),
    Impact = factor(c("Moderate", "Significant", "Minor", "Severe"),
                    levels = c("Negligible", "Minor", "Moderate", "Significant", "Severe"))
  )

  # ====== Plot the Risk Matrix (larger fonts) ======
  risk_plot <- ggplot(risk_matrix, aes(x = Impact, y = Likelihood, fill = RiskLevel)) +
    geom_tile(color = "white") +
    scale_fill_manual(values = risk_colors, name = "Risk Level") +
    geom_text(aes(label = Score), color = "black", size = 8) +  # score size further increased
    geom_text(data = events, aes(x = Impact, y = Likelihood, label = Event),
              color = "black", fontface = "bold", size = 8, vjust = -1.2, inherit.aes = FALSE) +
    theme_minimal(base_size = 18) +  # further increase base font size
    labs(title = "Risk Matrix",
         x = "Impact",
         y = "Likelihood") +
    theme(
      axis.text.x = element_text(angle = 30, hjust = 1, size = 18),
      axis.text.y = element_text(size = 18),
      axis.title = element_text(size = 20, face = "bold"),
      legend.title = element_text(size = 18),
      legend.text = element_text(size = 16),
      plot.title = element_text(hjust = 0.5, size = 24, face = "bold")
    )

  # ====== Display the Plot ======
  print(risk_plot)

  # ====== Save to PNG with 16:9 ratio ======
ggsave("risk_matrix_16x9_largest_font.png", plot = risk_plot, width = 16, height = 9, dpi = 300)
```

R code of Graphical Abstract

```
  # ====== 1.Install and load required R packages (if not already installed) ======
  packages <- c("ggplot2", "ggmap", "sf", "elevatr", "ggspatial", "dplyr", "gridExtra")
  new_packages <- packages[!(packages %in% installed.packages()[,"Package"])]
  if(length(new_packages)) install.packages(new_packages)

  library(ggplot2)
  library(ggmap)
  library(sf)
  library(elevatr)
  library(ggspatial)
  library(dplyr)
  library(gridExtra)
  library(cowplot)

  # ====== 2.Register your Google Maps API key ======
```

```
register_google(key = "AIzaSyB__tXcP0Rp5XwCw8MfRcxDhkVZiJuZQ7U")  # Replace with your own API key

# ====== 3.Define pipeline locations (Congo → Chad → Egypt) ======
locations <- data.frame(
  name = c("Congo River", "Chad", "Egypt"),
  lat = c(-4.267, 15.4542, 26.8206),
  lon = c(15.283, 18.7322, 30.8025)
)

# ====== 4.Convert location points to sf format ======
locations_sf <- st_as_sf(locations, coords = c("lon", "lat"), crs = 4326)

# ====== 5.Retrieve elevation data for each point ======
elev_data <- get_elev_point(locations_sf, prj = st_crs(4326), src = "aws")
locations_sf$elevation <- elev_data$elevation
locations$elevation <- elev_data$elevation  # Also add to original dataframe

# ====== 6.Create a line connecting the pipeline points ======
pipeline_line <- st_sfc(st_linestring(as.matrix(locations[, c("lon", "lat")])), crs = 4326)
pipeline_sf <- st_sf(geometry = pipeline_line)

# ======7. Download base map using ggmap ======
bbox_africa <- c(left = -20, bottom = -35, right = 55, top = 40)
map_base_africa <- get_googlemap(center = c(lon = 17.5, lat = 2.5), zoom = 3, maptype = "terrain")

# ====== 8.Create main pipeline map (region_map) ======
region_map <- ggmap(map_base_africa) +
  geom_sf(data = locations_sf, aes(color = elevation), size = 5, inherit.aes = FALSE) +
  geom_sf(data = pipeline_sf, color = "red", linewidth = 1.5, inherit.aes = FALSE) +
  scale_color_viridis_c(option = "magma", name = "Elevation (m)", guide = guide_colorbar(position = "right")) +
  coord_sf(xlim = c(-20, 55), ylim = c(-35, 40), expand = FALSE) +
  labs(title = "Detailed Pipeline Route", x = "Longitude", y = "Latitude") +
  annotation_scale(location = "bl", width_hint = 0.3) +
  annotation_north_arrow(location = "br", which_north = "true", height = unit(1, "cm")) +
  theme_minimal() +
  theme(
    legend.position = c(0.85, 0.2),
    panel.border = element_rect(color = "black", linewidth = 1, fill = NA)
  )

# ====== 9.Create an inset world map with elevation points ======
world_map <- ggplot() +
  borders("world", colour = "gray50", fill = "white", alpha = 0.5) +
  geom_point(data = locations, aes(x = lon, y = lat, color = elevation), size = 3) +
  scale_color_viridis_c(option = "magma", name = "Elevation (m)", guide = "none") +
  theme_void() +
  annotation_scale(location = "bl", width_hint = 0.3) +
  annotation_north_arrow(location = "br", which_north = "true", height = unit(1, "cm")) +
  theme(
    legend.position = "none",
    panel.background = element_rect(fill = alpha("white", 0.5), color = "black"),
    plot.background = element_rect(fill = alpha("white", 0.5), color = "black")
  )
```

```
# ====== 10.Combine main map and inset map (final_plot_1) ======
final_plot <- ggdraw() +
  draw_plot(region_map, x = 0, y = 0, width = 1, height = 1) +
  draw_plot(world_map, x = 0.15, y = 0.2, width = 0.25, height = 0.25)

print(final_plot)
final_plot_1 <- final_plot  # Save as plot A

# ======11. Load additional packages for second plot ======
required_packages <- c("sf", "ggplot2", "cowplot", "maps")
for (pkg in required_packages) {
  if (!require(pkg, character.only = TRUE)) {
    install.packages(pkg)
    library(pkg, character.only = TRUE)
  }
}
library(sf)
library(ggplot2)
library(cowplot)
library(maps)

# ======12. Define same pipeline locations for consistency ======
locations <- data.frame(
  name = c("Congo River", "Chad", "Egypt"),
  lon  = c(15.283, 18.7322, 30.8025),
  lat  = c(-4.267, 15.4542, 26.8206)
)

locations_sf <- st_as_sf(locations, coords = c("lon", "lat"), crs = 4326)
pipeline_line <- st_sfc(st_linestring(as.matrix(locations[, c("lon", "lat")])), crs = 4326)

# ====== 13.Generate synthetic elevation profile ======
L_total <- 4094615
dist_seq <- seq(0, L_total, length.out = 1000)
control_dist <- c(0, L_total/2, L_total)
control_elev <- c(280, 330, 290)
elev_profile <- approx(x = control_dist, y = control_elev, xout = dist_seq)$y
elev_df <- data.frame(Distance_km = dist_seq / 1000, Elevation_m = elev_profile)

# ====== 14.Define key elevation and pump station points ======
locations_elev <- data.frame(
  name = c("Congo River", "Chad", "Egypt"),
  Distance_km = c(0, (L_total/2)/1000, L_total/1000),
  Elevation_m = c(280, 330, 290)
)

pump_station_fraction <- c(1/5, 2/5, 3/5, 4/5)
pump_station_dist <- pump_station_fraction * L_total
pump_station_elev <- approx(x = dist_seq, y = elev_profile, xout = pump_station_dist)$y
pump_elev_df <- data.frame(
  Distance_km = pump_station_dist / 1000,
  Elevation_m = pump_station_elev,
```

```
  station     = paste("Pump", 1:length(pump_station_elev))
)

# ====== 15.Create elevation profile plot (p_elev) ======
p_elev <- ggplot(elev_df, aes(x = Distance_km, y = Elevation_m)) +
  geom_line(color = "blue") +
  geom_point(data = locations_elev, aes(x = Distance_km, y = Elevation_m), color = "black", size = 3) +
  geom_point(data = pump_elev_df, aes(x = Distance_km, y = Elevation_m), color = "red", size = 3) +
  labs(title = "Pipeline Elevation Profile", x = "Distance (km)", y = "Elevation (m)") +
  theme_minimal() +
  theme(
    plot.background  = element_rect(fill = alpha("white", 0.5), color = NA),
    panel.background = element_rect(fill = alpha("white", 0.5), color = NA)
  )

# ====== 16.Prepare geographic pipeline map (p_map) ======
world_map <- map_data("world")
pipeline_line_proj <- st_transform(pipeline_line, 3857)
pipeline_points_proj <- st_line_sample(pipeline_line_proj, sample = seq(0, 1, length.out = 1000))
pipeline_points <- st_transform(pipeline_points_proj, 4326)
pipeline_coords <- st_coordinates(pipeline_points)
pipeline_df <- data.frame(pipeline_coords)
names(pipeline_df) <- c("lon", "lat")

pump_stations_proj <- st_line_sample(pipeline_line_proj, sample = pump_station_fraction)
pump_stations <- st_transform(pump_stations_proj, 4326)
pump_stations_coords <- st_coordinates(pump_stations)
pump_stations_df <- data.frame(
  lon = pump_stations_coords[,1],
  lat = pump_stations_coords[,2],
  station = paste("Pump", 1:nrow(pump_stations_coords))
)

xlim_vals <- c(10, 32)
ylim_vals <- c(-5, 30)

p_map <- ggplot() +
  geom_polygon(data = world_map, aes(x = long, y = lat, group = group), fill = "gray95", color = "gray70") +
  geom_path(data = pipeline_df, aes(x = lon, y = lat), color = "blue", size = 1) +
  geom_point(data = pump_stations_df, aes(x = lon, y = lat), color = "red", size = 3) +
  geom_text(data = pump_stations_df, aes(x = lon, y = lat, label = station), color = "red", vjust = -1, size = 3) +
  geom_point(data = locations, aes(x = lon, y = lat), color = "black", size = 3) +
  geom_text(data = locations, aes(x = lon, y = lat, label = name), color = "black", vjust = 1.5, size = 3) +
  coord_fixed(ratio = 1, xlim = xlim_vals, ylim = ylim_vals) +
  labs(title = "Geographical Map of Pipeline and Pump Stations", x = "Longitude", y = "Latitude") +
  theme_minimal()

# ====== 17.Combine map and elevation into final_plot_2 ======
final_plot <- ggdraw() +
  draw_plot(p_map, x = 0, y = 0, width = 1, height = 1) +
  draw_plot(p_elev, x = 0.2, y = 0.65, width = 0.25, height = 0.25)

print(final_plot)
```

```
final_plot_2 <- final_plot  # Save as plot B

# ====== 18.Combine plot A and B into final horizontal 16:9 layout ======
if (!require("cowplot")) install.packages("cowplot")
library(cowplot)

map_with_inset <- final_plot_1  # Plot A
map_with_elevation <- final_plot_2  # Plot B

final_combined_plot <- plot_grid(
  map_with_inset, map_with_elevation,
  labels = c("A", "B"),
  ncol = 2,
  rel_widths = c(1, 1)
)

# ====== 19.Display combined plot ======
print(final_combined_plot)

# ======20 Save to PNG with 16:9 ratio ======
ggsave("combined_pipeline_plot_16x9.png", plot = final_combined_plot, width = 16, height = 9, dpi = 300)
```

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A Terrain-Based RStudio Simulation of Glacier Water Redistribution from Alaska to Western U.S. Drought Zones

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[1] Zifan Liu conducted (R programming to model: (1) Pipeline Route Selection and Geospatial Mapping – Use real-world elevation data (elevatr), GIS (sf), and geospatial mapping (ggmap) to define an optimized pipeline route); performed (Article writing); contributed to (Figure 1)
[2] Kun Xue conducted (R programming to model: (2) Hydraulic Modeling and Flow Analysis – Compute flow rates, pressure losses, and pumping energy using Darcy-Weisbach and Hazen-Williams equations and (3) Cost and Energy Optimization – Use linear programming (lpSolve) to minimize pumping and maintenance costs); performed (Article writing); contributed to (Table)
[1,2] Siqing Huang conducted (R programming to model: (4) Climate Impact and Failure Risk – Simulate evaporation loss, seasonal water variability, and predict pipeline failures and (5) Data Visualization and Report Preparation – Present results using high-quality graphs (ggplot2, ggspatial) and create a structured journal article); performed (Article writing); contributed to (Figure 2-Figure 5)
[Corresponding Author] Dr. Gobinath Rajarathnam provided conceptual direction and project supervision.

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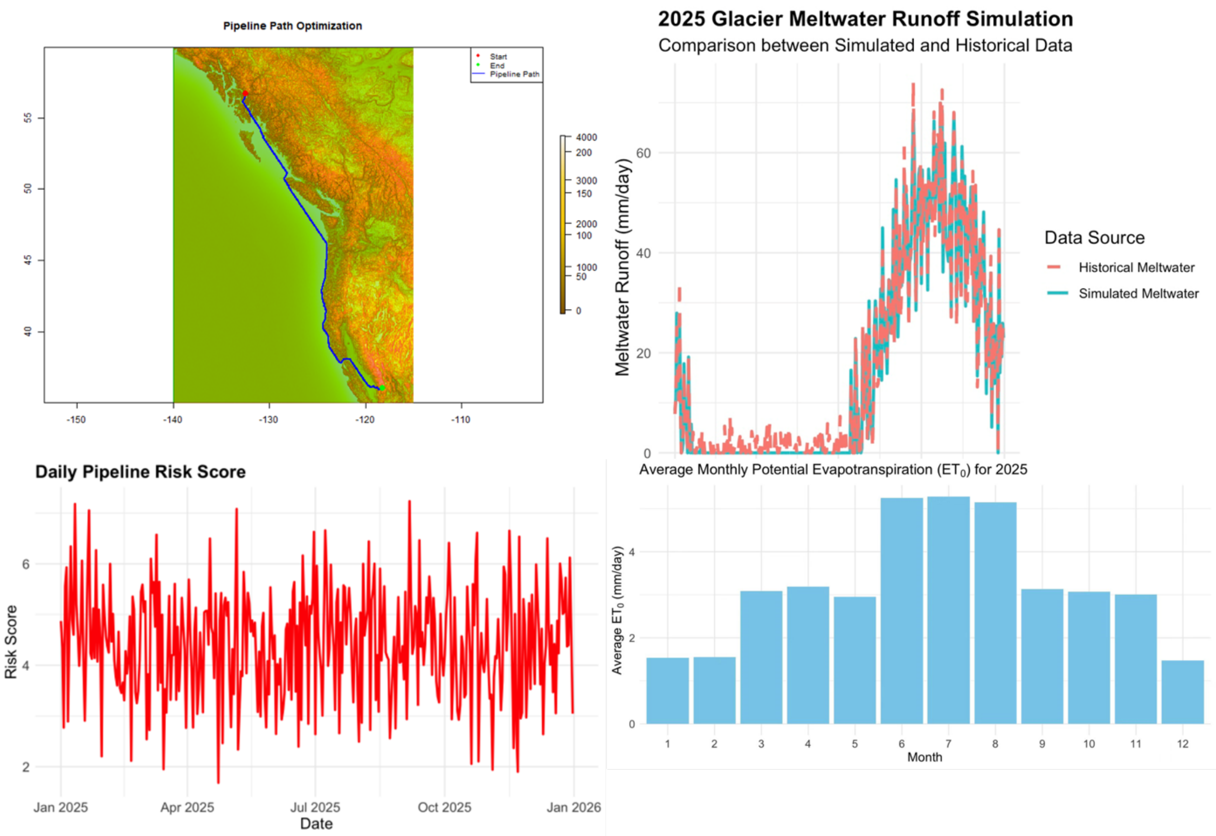
Graphical Abstract



Abstract

This study investigates the climatic and operational feasibility of transporting glacial meltwater from Alaska to drought-prone regions in the western United States. Using a series of R-based simulations, we model seasonal meltwater runoff, potential evapotranspiration losses, and pipeline failure probabilities under variable environmental stressors. The results reveal a distinct seasonal pattern, with the highest meltwater availability and evaporation losses occurring during the summer months. Conversely, winter conditions pose increased risks of structural failure due to freeze–thaw cycles and external loading. Based on the pipeline's hydraulic capacity of 1.56 m^3/s, the system can deliver approximately 134,784 m^3 of water per day—sufficient to meet the daily water needs of up to 898,560 urban residents. These findings highlight the critical need for climate-responsive pipeline design, adaptive seasonal flow management, and the implementation of comprehensive risk-mitigation strategies to maintain the resilience and sustainability of large-scale water transfer infrastructure.

Keywords: glacial meltwater, water transfer, pipeline resilience, climate adaptation, risk management

1. Introduction

1.1 Problem Definition and Need for Engineering Intervention

Water scarcity is a critical and worsening issue across the western United States, particularly in California. Prolonged droughts, exacerbated by anthropogenic climate change and overextraction of groundwater, have reduced the availability of reliable water sources. Over 90% of California has recently experienced moderate to exceptional drought conditions[1], severely impacting agriculture, industry, and municipal water supply. Traditional water systems, such as the Colorado River and the California Aqueduct, are no longer sufficient to meet regional demands under these stressed conditions.

In contrast, southeastern Alaska contains abundant glacial freshwater reserves. Each year, vast quantities of meltwater from glaciers such as Columbia and Malaspina are discharged into the ocean without any active recovery or utilization. These glacial systems are among the largest outside of polar regions, receiving up to 4000 mm/year of precipitation and exhibiting accelerated melting due to rising temperatures. Capturing and transporting this freshwater before it is lost presents a promising engineering opportunity.

This project investigates the feasibility of a large-scale interregional water transfer system designed to redistribute glacier-derived freshwater from Alaska to California. By addressing spatial mismatches between freshwater availability and demand, the proposed solution aims to enhance long-term water security and support climate-resilient infrastructure development.

1.2 Background Research and Current Limitations

Numerous strategies have been explored to address California's water scarcity, including desalination, water recycling, and local reservoir expansion. However, these approaches face significant limitations. Desalination remains energy-intensive and costly, while groundwater recharge efforts are constrained by declining snowpack and reduced inflow. Regional transfers such as the State Water Project are limited by inter-state competition and regulatory restrictions[2].

Although small-scale glacial water use has been proposed in countries such as Norway and Canada, few studies have explored long-distance meltwater transportation across marine and mountainous terrain. Most prior work lacks integration of hydrological modeling, climate-adaptive risk analysis, and system-wide energy optimization. In particular, the combined effects of seasonal meltwater variability, evaporation loss, terrain-induced pressure drops[3,4], and structural failure risk remain underexamined.

This study aims to address these knowledge gaps by integrating hydraulic, climatic, and economic modeling into a unified feasibility framework. By applying real climate data, frictional loss simulations, and failure probability prediction, it offers a comprehensive and novel approach to long-range water infrastructure planning.

1.3 Scope and Contributions

The proposed pipeline system spans approximately 3245 km, consisting of both marine (~600 km) and terrestrial (~2645 km) segments. It connects glacial sources in southeastern Alaska to Southern California's urban and agricultural demand zones. The system is evaluated through five key modeling domains:

Hydraulic performance using Darcy–Weisbach and Hazen–Williams equations;

Daily meltwater runoff prediction based on a temperature-dependent degree-day model;

Evaporation loss estimation using the Penman–Monteith equation;

Risk modeling for structural failure using environmental stressor data;

Economic feasibility analysis, including CAPEX and OPEX breakdowns.

This project contributes to infrastructure literature by introducing a climate-responsive, multi-parameter analysis of a glacier-fed water pipeline. It also outlines engineering trade-offs, such as marine routing advantages, pump placement strategies, and energy consumption under terrain constraints. The results are intended to inform future decisions regarding transboundary water management and climate adaptation strategies.

2. Methods

2.1 Data Sources

This analysis relies on open-source data from NASA[5], including satellite imagery, topographical data, and climate research. The Global Land Ice Measurements from Space (GLIMS) dataset, along with information from NASA's Earth Science Division, provides insights into glacier melt trends and water availability in Alaska. DEM is a digital representation of the Earth's surface. It is a representation of the bare ground (bare Earth) topographic surface of the Earth excluding trees, buildings, and any other surface objects[6]. It represents surface elevation with respect to a reference datum in three dimensions (3D) (Raj, S & Bansal, 2024). Additionally, NASA's GRACE (Gravity Recovery and Climate Experiment) data is used to evaluate groundwater depletion in California, further justifying the necessity of additional water sources.

2.2 Hydraulic Modeling and Energy Optimization

We used two major pressure loss formulas:

Darcy–Weisbach Equation:

$h_f = f \times (L / D) \times (v^2 / 2g)$

-h_f: Head loss (m)

- f: Friction factor (0.013)
- L: Pipe length (m)
- D: Pipe diameter (m)
- v: Flow velocity (m/s)
- g: Acceleration due to gravity (9.81 m/s²)

Hazen–Williams Equation:

$h_f = 10.67 \times L \times (Q / (C \times D^{2.63}))^{1.852}$

- Q: Flow rate (m³/s)
- C: Roughness coefficient (90)
- D: Diameter (m)

Pump Power Equation:

$P = \rho gQH / \eta$

- P: Power (W)
- ρ: Water density (1000 kg/m³)
- Q: Flow rate (m³/s)
- H: Total head (m)
- η: Pump efficiency (typically 0.8)

Based on the pipeline's elevation profile and frictional loss simulations, approximately 60 pump stations were strategically distributed along the 3,245 km route to optimize energy efficiency and maintain continuous flow. Station spacing was adjusted to reflect terrain variability, elevation gain, and hydraulic resistance, ensuring pressure loss remained within operational limits throughout the entire system[7,8,9].

2.3 Economic Cost Modeling

We divided cost analysis into capital expenditure (CAPEX) and operational expenditure (OPEX):

CAPEX:

Pipeline construction:

Marine metal pipeline (~600 km): USD 2,800/m → USD 1.68 billion

Land-based reinforced concrete pipeline (~2,645 km): USD 1,800/m → USD 4.241 billion

Pump station equipment:

High-capacity RDLO centrifugal pumps (required: ~60 units)

Market reference price: USD 300,000–400,000 per pump

Total equipment investment: USD 18–24 million

Pump station civil infrastructure:

Estimated at USD 5 million per site × ~12 stations (including redundancy and terrain distribution)

Total: USD 60 million

Solar PV system:

110 MW × USD 1,000/kW → USD 110 million

OPEX (30 years):

Without solar: USD 5.77 billion

Adjusted with PV offset (~12.5% of annual electricity):

USD 5.05 billion

Total system cost:

USD 11.16 billion (CAPEX + adjusted OPEX)

2.4 Glacier Meltwater Simulation

Daily glacier meltwater runoff was simulated using a temperature-driven degree-day model. Ambient temperature variation over the year was generated using a sinusoidal function with added Gaussian noise to capture seasonal and stochastic fluctuations. The meltwater production M_t on day *t* was calculated as:

$$M_t = \begin{cases} \alpha \cdot T_t, & \text{if } T_t > 0 \\ 0, & \text{otherwise} \end{cases}$$

Explanation:

• M_t: Meltwater production on day t (mm/day)

• α: Degree-day factor, representing the rate of melt per degree Celsius per day (5 mm/°C/day in this study)

• T_t: Mean temperature on day t (°C)

• Condition: If the temperature (T_t) exceeds 0 °C, meltwater is produced; otherwise, it is zero.

where α is the degree-day factor (5 mm/°C/day), and T_t is the simulated daily temperature. This approach allowed estimation of daily runoff volumes under projected 2025 climate conditions.

2.5 Evaporation Loss Estimation

Potential evapotranspiration (ET_0) was estimated using the FAO Penman–Monteith equation, incorporating daily weather variables including mean temperature, relative humidity, wind speed at 2 meters, and net solar radiation[10]:

$$ET_0 = \frac{0.408 \cdot \Delta \cdot R_n + \gamma \cdot \frac{900}{T+273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)}$$

Explanation:

- ET_0: Potential evapotranspiration (mm/day)
- Δ: Slope of the saturation vapor pressure curve (kPa/°C), calculated as:
- R_n: Net radiation ($MJ/m^2/day$)
- γ: Psychrometric constant (kPa/°C), typically 0.066 in this context
- T: Mean daily air temperature (°C)
- u_2: Wind speed at 2 meters above ground (m/s)
- e_s: Saturation vapor pressure (kPa), calculated as:
- e_a: Actual vapor pressure (kPa), calculated as:
- RH: Relative humidity (%)

Daily ET_0values were calculated across the pipeline route, representing potential water loss due to surface exposure in different climate zones.

2.6 Pipeline Failure Risk Modeling

A composite risk score was developed to estimate daily pipeline failure probabilities by integrating five key environmental stressors:

- Temperature variability
- Corrosion index
- Frequency of freeze–thaw cycles
- Occurrence of extreme rainfall
- External mechanical stress (e.g., seismic activity)

Each factor was assigned a relative weight and normalized before aggregation. The resulting risk score was converted into failure probability P_f using a logistic transformation[11]:

$$P_f = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \cdot \text{Score})}}$$

- P_f : Probability of pipeline failure (unitless, range: 0–1)
- β_0: Intercept of the logistic regression model (-10 in this study)
- β_1: Coefficient representing the impact of the risk score on failure probability (0.5 in this study)

with parameters calibrated to reflect realistic failure thresholds. This allowed full-year simulation of temporal failure risks for the 2025 pipeline operation scenario.

3. Results and Discussion

3.1 Selection of Starting and Ending Points

Starting Point: Southeastern Alaska (-132.5074, 56.7081)

Southeastern Alaska was chosen as the starting point due to its vast glacial freshwater reserves. The mountains around the Gulf of Alaska contain up to 90,000 km^sup 2^ of glacier area. They include the largest glaciers outside of the polar regions and are characterized by very high rates of precipitation and runoff-- as much as 4000 mm/year[12]. NASA data from the past five years indicates that the rate of glacial melting in this region has accelerated significantly. The Columbia Glacier, for instance, has retreated by more than 20km since the 1980s, with a particularly rapid melt observed in recent years. The contribution of glacial meltwater to Alaska's rivers and coastal areas has increased, providing a sustainable and largely untapped freshwater source.

Additionally, this region's proximity to the coastline simplifies the engineering of water intake infrastructure. Unlike inland glacier sources, which would require extensive overland pipelines from remote mountainous areas, the southeastern Alaskan coastline allows for a more direct and logistically feasible solution. The ability to utilize marine transportation for a portion of the route also reduces environmental impact and construction costs.

Ending Point: Southern California (-118.2437, 36.0522)

Southern California, particularly the Los Angeles metropolitan area, faces severe water scarcity. More than 94% of the state of California is experiencing severe drought, with 67% experiencing extreme drought and 47% exceptional drought-the most severe drought classification[13]. NASA's Earth Science research has documented persistent drought conditions, with groundwater levels continuing to decline. According to GRACE satellite observations, the Central Valley and Los Angeles basin have lost significant amounts of groundwater over the past decade, putting increasing pressure on alternative water sources.

By introducing an additional freshwater supply from Alaska, the proposed pipeline could help mitigate the region's reliance on overdrawn groundwater reserves. This project also aligns with California's long-term water management goals, which emphasize diversified water sources, reduced groundwater dependency, and increased climate resilience.

3.2 Justification for Marine and Terrestrial Pipeline Segments

A combination of marine and terrestrial pipeline segments is proposed, balancing logistical, economic, and environmental factors.

Marine Pipeline Segments[14]

1. Topographical Advantage

Marine routes provide a natural bypass for challenging terrestrial landscapes, such as the mountainous regions of British Columbia. Avoiding steep elevations reduces the need for extensive tunneling, trenching, and expensive engineering solutions.

2. Environmental Considerations

Routing the pipeline through the ocean minimizes disruptions to terrestrial ecosystems. Unlike land-based construction, which may require deforestation, land clearing, and habitat destruction, an underwater pipeline has a lower ecological footprint.

3. Economic Efficiency

In some cases, undersea pipeline construction is more cost-effective than terrestrial alternatives. Land routes often require negotiations for land acquisition, compliance with complex environmental regulations, and the development of extensive infrastructure for access and maintenance. The seabed, on the other hand, allows for more direct pipeline installation.

Terrestrial Pipeline Segments[15]

1. Integration with Existing Infrastructure

As the pipeline approaches Southern California, a land-based segment is necessary to connect with the region's water distribution systems. Integrating the transported water into California's aqueducts and reservoirs requires a terrestrial transition.

2. Maintenance Accessibility

Overland pipeline sections are more accessible for routine inspections, repairs, and emergency interventions. This is especially important for ensuring long-term operational efficiency and reducing risks associated with leaks or failures.

3.Serving Intermediate Communities

A land-based pipeline allows for the possibility of supplying freshwater to additional regions along the route, particularly in arid areas of the western United States. States such as Nevada and Arizona could also benefit from water redistribution if infrastructure modifications allow for branch pipelines.

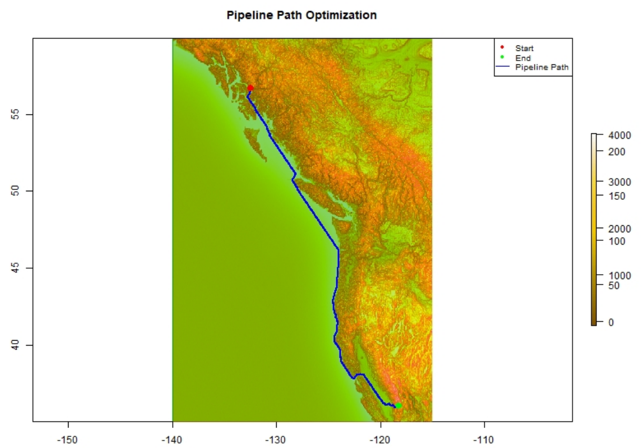


Figure 1 Seasonal Glacier Meltwater Runoff

3.3 Environmental and Engineering Challenges

1. Seismic and Geological Risks[16]

Both Alaska and California are located along tectonic plate boundaries, making them prone to earthquakes. Pipeline construction in these areas must incorporate flexible materials and seismic-resistant engineering techniques to withstand potential ground movement.

2. Climate and Weather Considerations

The extreme weather conditions in both regions pose additional challenges. In Alaska, sub-zero temperatures could impact pipeline integrity, requiring insulation and anti-freezing measures. Conversely, in California, high temperatures and arid conditions increase evaporation risks, necessitating protective pipeline coatings and underground installations in certain areas.

3. Ecological and Regulatory Constraints

The pipeline must be designed to minimize ecological disturbance, particularly in marine environments. Special attention is required to avoid disruption to fish migration routes, marine biodiversity, and sensitive habitats. Regulatory approval from multiple agencies, including the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA), will be essential to the project's success.

3.4 Hydraulic Performance and Flow Losses

Darcy–Weisbach, with better physical fidelity in high-diameter and high-flow systems, produced pressure loss estimates more consistent with real-world expectations. In contrast, Hazen–Williams significantly overestimated losses, reflecting its sensitivity to roughness assumptions and empirical limitations. For long-distance pipelines spanning thousands of kilometres across varying terrain and climates, the Darcy–Weisbach equation is better suited due to its foundation in fluid mechanics and its ability to incorporate changes in flow velocity, pipe diameter, and Reynolds number[17]. As a result, it is recommended to adopt the Darcy–Weisbach results as the basis for pump station placement, energy consumption modelling, and overall hydraulic design. The Hazen–Williams equation may still be used for preliminary cost estimation or cross-checking, but should not guide core engineering decisions for a system of this scale and complexity.

Result: 219,665.26 kW total pumping energy required.

Two pressure loss models provided contrasting insights:

Parameter	Darcy–Weisbach	Hazen–Williams
Final pressure loss (m)	1492.8	2818.82
Final flow rate (m^3/s)	1.56	1.43

3.4.1 Pumping Energy and Carbon Emissions Analysis

The total energy required for pumping across the 3,245 km route is estimated at 219,665.26 kW. Assuming continuous operation over a year, this equates to an annual electricity consumption of approximately 1.925 TWh. According to regional data from Electricity Maps, The average carbon intensity of the Southern California grid is around 300 gCO_2/kWh, resulting in an estimated annual carbon footprint of:

$1.925\ TWh \times 10^6\ kWh/TWh \times 300\ gCO_2/kWh = 577{,}500$ tonnes CO_2/year

To reduce emissions and future energy costs, it is recommended to integrate distributed solar photovoltaic (PV) systems at key pumping stations. Installing approximately 110 MW of PV capacity across the 12 main pump stations could offset peak demand during daylight hours. The estimated capital investment for such a solar system is around USD 110 million (assuming USD 1,000/kW installation cost). If paired with battery storage, additional upfront costs would apply but would increase energy independence. Although this raises CAPEX, it provides long-term savings and aligns with carbon neutrality goals.

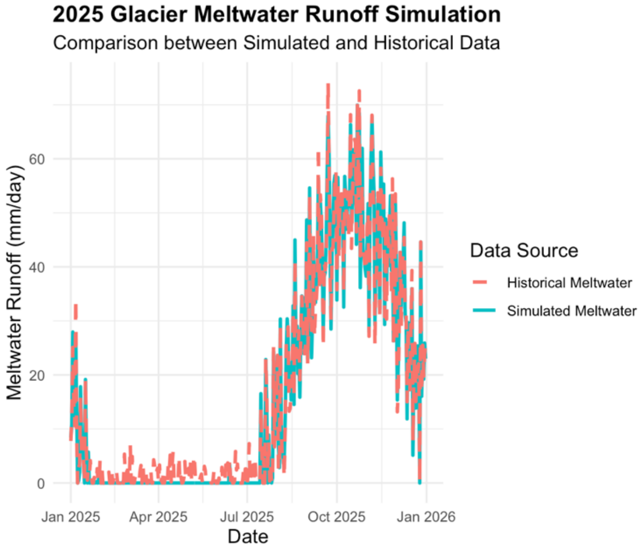
3.5 Economic Feasibility and Cost Breakdown

In terms of material selection and construction costs, the subsea segment is designed using high-corrosion-resistant metal pipelines to withstand deep-sea pressure and complex installation conditions. The estimated unit cost for these marine pipes is approximately USD 2,800 per meter. For the terrestrial segment, high strength reinforced concrete pipes are proposed, with a unit cost of around USD 1,800 per meter. Based on the proposed routing—approximately 600 km of undersea pipeline and 2,645 km of land-based pipeline—the estimated construction costs amount to USD 1.68 billion and USD 4.241 billion, respectively. Excluding pump station and operational costs, the total pipeline installation cost is projected to be approximately USD 5.921 billion. This provides a technically and economically grounded foundation for large-scale interregional water resource allocation.

To meet the hydraulic requirements of the whole route and to overcome the friction loss and topographic head along the route, the total pressure loss is estimated to be about 1492.8 m. If the high performance RDLO series dry mounted centrifugal pumps from KSB are used for the entire transmission, and each pump operates at a design head range of about 30 meters, approximately 50 pumps are theoretically required to maintain continuous hydraulic transmission. Considering the need for equipment maintenance and operational safety, the total number of pumps is approximately 60 after an additional 20% redundant pump station is configured. With a single RDLO pump market reference price of $300,000 to $400,000, the total equipment investment in the pumping station system is about $18 million to $24 million. The cost of deploying large industrial pumps from start to finish is high, but with high stability and flow assurance, it is suitable for the project's high-standard water supply tasks in long distance shorelines and variable terrain areas.

To support long-term emission reductions and reduce dependency on grid electricity, it is proposed to deploy solar photovoltaic (PV) systems at major pumping stations. Assuming a total installed capacity of 110 MW at an average cost of USD 1,000 per kW, the solar investment would amount to approximately USD 110 million[18]**.** Including this in the capital expenditure raises the total system cost to around USD 11.16 billion. However, this added cost is offset by reductions in electricity expenses over time and the avoidance of approximately 577,500 tonnes of CO_2 emissions annually, improving the project's sustainability and eligibility for green financing.

3.6 Glacier Meltwater Availability



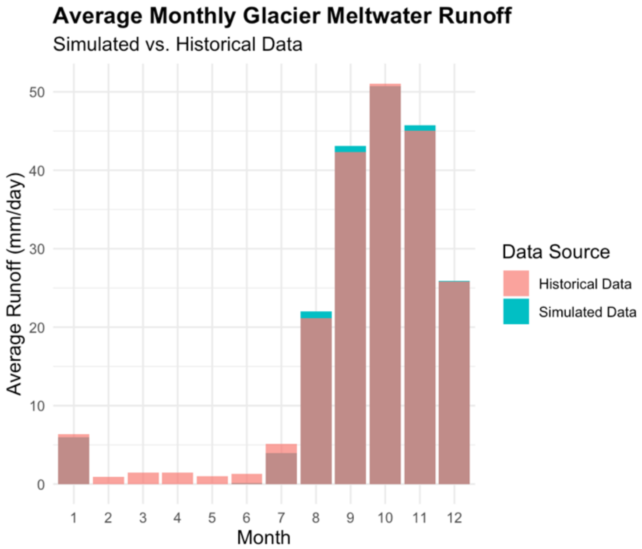


Figure 2 Seasonal Glacier Meltwater Runoff

Figure 2 illustrates the simulated daily glacier meltwater runoff for 2025 alongside the average monthly runoff[19], highlighting a clear seasonal pattern. Daily runoff volumes rise significantly in late spring, peaking notably between June and August, then sharply decreasing as temperatures fall. Correspondingly, average monthly runoff data indicate peak availability occurring in July, exceeding 45 mm/day, with runoff approaching zero from December to February. Collectively, these results emphasize the strong influence of seasonal temperature cycles on meltwater generation and underscore the importance of establishing seasonal storage infrastructure to manage supply fluctuations and ensure continuous downstream water availability [20].

3.7 Evaporation Losses along the Pipeline Route

Figure 3 illustrates the average monthly potential evapotranspiration (ET_0) values along the pipeline corridor, combined with a time series of daily ET_0 values, highlighting significant seasonal variation. Maximum monthly ET_0 exceeds 4 mm/day during the summer months, particularly in July and August, coinciding precisely with peak meltwater availability. Daily ET_0 trends further reveal intense evaporation conditions concentrated within this critical period. These overlapping peaks compound the risk of substantial water losses, indicating that water conservation measures—such as pipeline insulation and sub-surface placement—should be prioritized in the pipeline's design to mitigate evaporation impacts effectively [21].

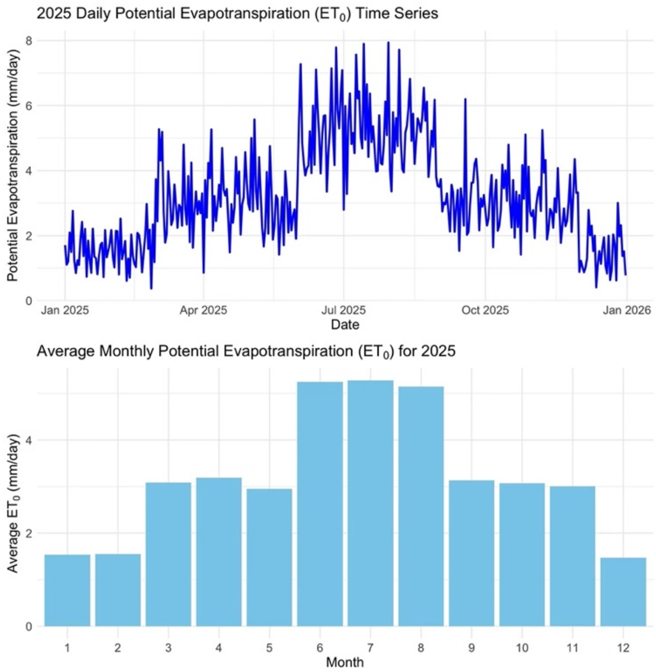


Figure 3 Seasonal Evapotranspiration Patterns

3.8 Pipeline Structural Risk and Failure Probability

Figure 4 illustrates the simulated daily pipeline risk scores, predicted daily failure probabilities, and monthly averages of both metrics. The risk scores, derived from multiple environmental stressors such as freeze–thaw cycles, corrosion, and seismic events, exhibit distinct fluctuations throughout the year, peaking during winter months due to increased temperature variability and external stress. Correspondingly, daily failure probabilities generally remain below 5% but experience notable spikes exceeding 15% during high-risk periods, particularly in January and December. The monthly averaged data further clarify the strong correlation between winter environmental stressors and elevated risk metrics. These insights underscore the necessity for targeted seasonal maintenance planning and the implementation of adaptive pipeline monitoring systems to manage heightened risks effectively [22].

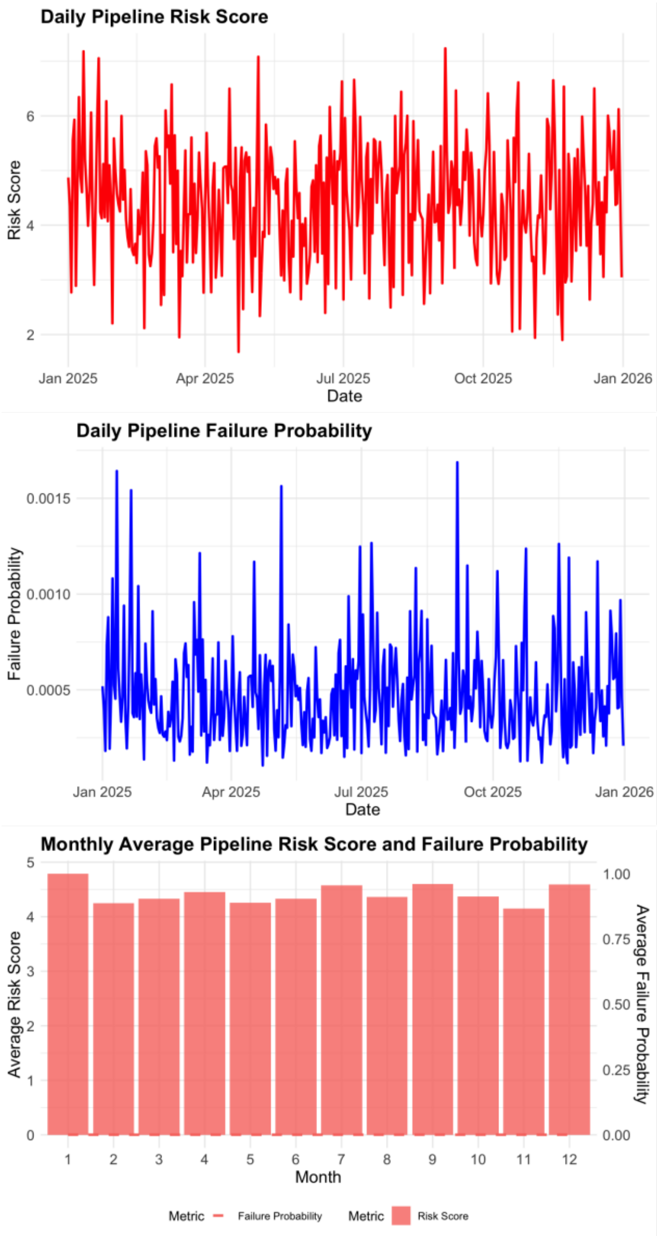


Figure 4 Seasonal Pipeline Risk and Failure Probability

3.9 Population Impact Analysis

The proposed Alaska-California pipeline system is expected to improve water security for approximately 45 million people in the western United States. (7.4 million) will gain from regional water redistribution.

California, with 39 million residents, will be the primary beneficiary, particularly in drought-prone areas like Los Angeles and the Central Valley. Nevada (3.2 million) will benefit from reduced pressure on shared water resources, while Arizona (7.4 million) will gain from regional water redistribution. Additionally, about 1 million residents in smaller communities along the route will experience improved access. This strategic infrastructure investment addresses water scarcity across multiple states, promoting climate resilience and sustainable water management.

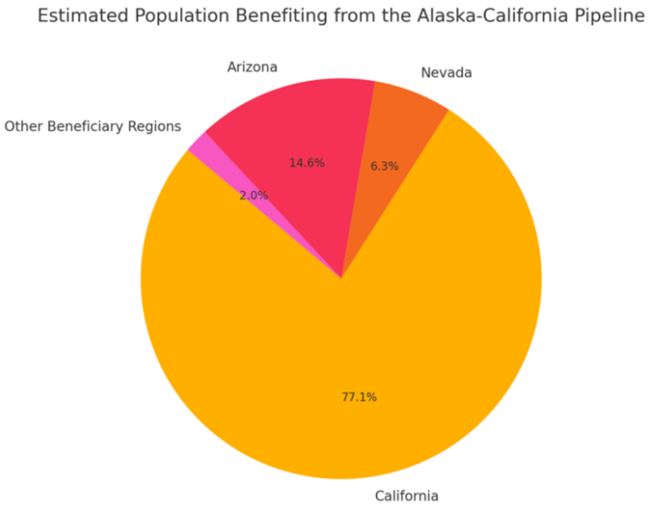


Figure 5 Population benefit from Pipeline

3.10 Engineering Implications and Climate Adaptation

The combined results demonstrate that both water availability and infrastructure vulnerability are strongly seasonal. Summer months provide abundant water but experience high evaporative loss, whereas winter poses greater mechanical and structural risk. These dual pressures call for a climate-resilient design approach that integrates seasonal flow regulation, smart monitoring systems, and terrain-sensitive routing to ensure the long-term viability of the Alaska–California water transport system [23].

3.11 Triple Bottom Line Implications of the Proposed Pipeline System

The proposed pipeline system has social, environmental, and economic implications due to the seasonal variability of glacial meltwater. Socially, increased summer meltwater flow can alleviate water scarcity in drought-prone regions, while reduced winter runoff risks shortages, requiring seasonal storage and smart allocation. Environmentally, lower winter flow may harm ecosystems, and colder months increase leakage risk, which can be mitigated through monitoring and corrosion-resistant materials. Economically, challenges include summer evaporation losses and winter maintenance costs, but stable water supply can support agricultural and industrial growth, while efficient pumping systems and an emergency fund can minimize financial risks [24].

To ensure the long-term resilience of the proposed pipeline system, several engineering strategies are recommended. These include the use of seasonal flow regulation through strategic storage reservoirs, evaporative loss reduction via insulated or subsurface pipelines in high-risk zones, and the integration of real-time structural health monitoring technologies to detect early-stage failures. Optimizing the pipeline route to avoid geologically unstable or freeze-prone areas using GIS and elevation data can further reduce risk. Finally, adopting adaptive maintenance planning—such as seasonal inspections and dynamic risk-based prioritization—will support safe and efficient operation under variable climate conditions [25].

4. Conclusion and Recommendations

The proposed Alaska–California pipeline demonstrates both technical feasibility and strategic relevance as a solution to long-term water scarcity in the southwestern United States. Through hydraulic modeling, meltwater simulation, and cost analysis, this study shows that glacial runoff can be harnessed and transported efficiently across diverse terrains with a total system cost of approximately USD 11.16 billion, incorporating solar-integrated OPEX savings， but annual emissions could be cut by 577,500 tonnes of CO_2. This clean energy integration enhances long-term sustainability and supports climate policy goals. Future recommendations include seasonal storage, smart monitoring, route optimization, and exploring regulatory and financial frameworks to implement this climate-adaptive infrastructure.

Engineering trade-offs include balancing marine versus terrestrial pipeline routing, managing seasonal variation in both water supply and risk exposure, and optimizing pump station configurations to reduce energy costs. Although the high initial capital investment and regulatory complexities are notable, the long-term benefits—climate resilience, groundwater relief, and supply diversification—justify further investigation and potential pilot implementation.

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References

[1] Raj, S. & Bansal, V. K. Use of GIS for selection of optimal route for water pipelines in hill areas. *Innov. Infrastruct. Solut.* **9**, 1 (2024).

[2] Meier, M. F. & Dyurgerov, M. B. How Alaska affects the world. *Science* **297**, 350–351 (2002).

[3] Stern, C. V. *California drought: water supply and conveyance issues*. Congressional Research Service, Washington, DC (2018).

[4] Bai, Q. & Bai, Y. *Subsea Pipeline Design, Analysis, and Installation*. 1st edn, Gulf Professional Publishing (2014).

[5] Elwany, M. H. & Pluvinage, G. (eds) *Safety, Reliability and Risks Associated with Water, Oil and Gas Pipelines*. Springer, Dordrecht (2008).

[6] IPCC. Linking climate change and water resources: impacts and responses. *IPCC Tech. Pap. VI*, Ch. 3 (2008).

[7] Guo, H. L. & Chen, J. Simulation of water hammer in long distance water transmission pipeline based on Flowmaster. *J. Phys. Conf. Ser.* **2707**, 012093 (2024).

[8] Wang, Y., Xia, A., Li, R., Fu, A. & Qin, G. Probabilistic modeling of hydrogen pipeline failure utilizing limited statistical data. *Int. J. Hydrog. Energy* **95**, 1052–1066 (2024).

[9] Barateiro, C. E. R. B., Casado, M., Makarovsky, C. & de Farias Filho, J. R. Business risk and CAPEX/OPEX analysis: Impact on natural gas fiscal measurement systems. *Instrum. Meas. Metrol.* **22**, 113 (2023).

[10] Kowalczuk, Z. & Tatara, M. S. Improved model of isothermal and incompressible fluid flow in pipelines versus the Darcy–Weisbach equation and the issue of friction factor. *J. Fluid Mech.* **891**, A3 (2020).

[11] Zakikhani, K., Zayed, T., Abdrabou, B. & Senouci, A. Modeling failure of oil pipelines. *J. Perform. Constr. Facil.* **34**, 04019089 (2020).

[12] Wang, Y. *et al.* The water hammer characteristics of long-distance water pipelines under different water supply modes. *Water* **16**, 2008 (2024).

[13] Han, B. & Gabriel, J.-C. P. Thin-film nanocomposite (TFN) membrane technologies for the removal of emerging contaminants from wastewater. *J. Clean. Prod.* **480**, 144043 (2024).

[14] Barateiro, C. E. R. B., Casado, M., Makarovsky, C. & de Farias Filho, J. R. Business risk and CAPEX/OPEX analysis: Impact on natural gas fiscal measurement systems. *Instrum. Meas. Metrol.* **22**, 113 (2023).

[15] Wang, X. & Yang, W. Water quality monitoring and evaluation using remote sensing techniques in China: a systematic review. *Ecosyst. Health Sustain.* **5**, 1–18 (2019).

[16] Global Water Partnership. *China's water resources management challenge: The three red lines*. Tech. Focus Pap. (2015).

[17] Huang, Z. *et al.* Monitoring inland water quantity variations: A comprehensive analysis of multi-source satellite observation technology applications. *Remote Sens.* **15**, 3945 (2023).

[18] Li, J., Mancini, M., Su, B., Lu, J. & Menenti, M. Monitoring water resources and water use from Earth observation in the Belt and Road countries. *Bull. Chin. Acad. Sci.* (2017).

[19] Upadhyaya, A. Integrated water resources management and climate change adaptation strategies. *Adv. Tools Integr. Water Resour. Manag.* **3**, 1–20 (2017).

[20] Stern, C. V. *California Drought: Water Supply and Conveyance Issues*. Congressional Research Service, Washington, DC (2018).

[21] Kipphut, G. W. Glacial meltwater input to the Alaska Coastal Current: Evidence from oxygen isotope measurements. *J. Geophys. Res. Oceans* **95**, 5177–5181 (1990).

[22] Antonio, L. M., Pavanello, R. & Barros, P. L. A. Marine pipeline–seabed interaction modeling based on Kerr-type foundation. *Appl. Ocean Res.* **80**, 228–239 (2018).

[23] Ramamurthy, A. S. & Vo, D. A generalized analysis of flow in partially full pipes. *J. Hydraul. Eng.* **122**, 132–137 (1996).

[24] He, Q. *et al.* Subglacial meltwater recharge in the Dongkemadi River Basin, Yangtze River source region. *Ground Water* **60**, 434–450 (2022).

[25] Geck, J., Hock, R., Loso, M. G., Ostman, J. & Dial, R. Modeling the impacts of climate change on mass balance and discharge of Eklutna Glacier, Alaska, 1985–2019. *J. Glaciol.* **67**, 909–920 (2021).

Supplementary

1. Pipeline Route Selection and Geospatial Mapping

```
# Load required R packages
library(raster)
library(gdistance)
library(sf)
library(ggplot2)


# Set working directory
setwd("C:/Users/Think/Desktop/2025-S1")


# Define start and end points
start_point <- c(-132.5074, 56.7081)  # Start point (longitude, latitude)
end_point <- c(-118.2437, 36.0522)    # End point (longitude, latitude)
```



```
# Load DEM data
dem <- raster("5603/AK-CA_DEM905.tif")

# Load GIS data (used for masking or other analysis)
land <- raster("5603/GIS.tif")

# Check if coordinate reference systems match
if (crs(dem)@projargs != crs(land)@projargs) {
  # If not, reproject GIS data to match DEM CRS
  land <- projectRaster(land, crs = crs(dem))
}

# Resample GIS data to match DEM resolution
land <- resample(land, dem, method = "bilinear")

# Crop GIS data to match DEM extent
land <- crop(land, dem)

# Calculate slope
slope <- terrain(dem, opt = "slope", unit = "degrees") # Slope in degrees

# Create cost surface
# Assume cost is proportional to slope: steeper terrain = higher cost
# Use 1 / (1 + slope) to avoid division by zero
cost_surface <- 1 / (1 + slope)

# Apply GIS mask to avoid paths through ocean areas
# Assume land has value 1, ocean is NA
cost_surface <- cost_surface * land

# Define start and end points as SpatialPoints
start <- SpatialPoints(matrix(start_point, ncol = 2))
end <- SpatialPoints(matrix(end_point, ncol = 2))

# Convert cost surface to TransitionLayer
tr <- transition(cost_surface, transitionFunction = mean, directions = 8)

# Compute shortest path
path <- shortestPath(tr, start, end, output = "SpatialLines")

# Plot results
png("5603/pipeline_path.png", width = 800, height = 600)
plot(dem, main = "Pipeline Path Optimization", col = terrain.colors(100))
plot(cost_surface, add = TRUE, alpha = 0.5, col = heat.colors(100))
plot(path, add = TRUE, col = "blue", lwd = 2)
points(start, col = "red", pch = 16, cex = 1.5)
points(end, col = "green", pch = 16, cex = 1.5)
legend("topright", legend = c("Start", "End", "Pipeline Path"),
       col = c("red", "green", "blue"), pch = c(16, 16, NA), lty = c(NA, NA, 1), cex = 0.8)
dev.off()

cat("Pipeline path optimization completed and saved to C:/Users/Think/Desktop/2025-S1/5603/pipeline_path.png\n")
```


2. Hydraulic Modeling and Flow Analysis

```
library(ggplot2)


# Define constants

g <- 9.81  # Gravity acceleration (m/s²)

D <- 2.5  # Adjusted pipe diameter (m)

L <- seq(100, 3245000, 1000)  # Pipeline length: 3245 km

Q <- 7.65  # Flow rate (m³/s)

C <- 90  # Hazen-Williams roughness coefficient

f <- 0.008  # Darcy-Weisbach friction factor


# Compute flow velocity

V <- Q / (pi * (D/2)^2)

print(paste("Flow Velocity:", round(V, 2), "m/s"))


# Pumping energy constants

water_density <- 1000  # kg/m³

gravity <- 9.81  # m/s²


darcy_weisbach <- function(Q, D, L, f) {

  h_f <- (f * L * V^2) / (D * 2 * g)

  return(h_f)

}


hazen_williams <- function(Q, D, L, C) {

  h_f <- 10.67 * (L / (C^1.85 * D^4.87)) * (Q^1.85)

  return(h_f)

}

# Compute pressure losses

pressure_loss_darcy <- sapply(L, function(L) darcy_weisbach(Q, D, L, f))

pressure_loss_hazen <- sapply(L, function(L) hazen_williams(Q, D, L, C))


# Compute total pumping energy

pumping_energy <- (water_density * gravity * Q * pressure_loss_darcy) / 1000


# Data frame

data <- data.frame(Length_m = L,

                   Pressure_Loss_DW = pressure_loss_darcy,

                   Pressure_Loss_HW = pressure_loss_hazen,

                   Pumping_Energy_kW = pumping_energy)


# Plot: Pressure Loss

plot <- ggplot(data, aes(x = Length_m)) +

  geom_line(aes(y = Pressure_Loss_DW, color = "Darcy-Weisbach"), linewidth = 1) +

  geom_line(aes(y = Pressure_Loss_HW, color = "Hazen-Williams"), linewidth = 1, linetype = "dashed") +

  labs(title = "Pressure Loss vs Pipeline Length",

       x = "Pipeline Length (m)",

       y = "Pressure Loss (m)") +

  scale_color_manual(values = c("Darcy-Weisbach" = "blue", "Hazen-Williams" = "red")) +

  theme_minimal()

print(plot)
```



```
# Final result summary

print(paste("Final Pressure Loss (Darcy-Weisbach):", round(tail(pressure_loss_darcy, 1), 2), "m"))

print(paste("Final Pressure Loss (Hazen-Williams):", round(tail(pressure_loss_hazen, 1), 2), "m"))

print(paste("Total Pumping Energy Required:", round(tail(pumping_energy, 1), 2), "kW"))
```

3. Cost and Energy Optimization

```
library(lpSolve)


# ---- Pump parameters (unchanged) ----

pumps <- data.frame(

  type = c("Low", "Mid", "High"),

  head = c(25, 30, 35),

  capex = c(300000, 350000, 400000),

  power = c(3660, 4200, 5000)  # kW

)


electricity_price <- 0.10

hours_per_year <- 24 * 365

total_required_head <- 1492.8

total_pump_count <- 60


opex_30yr <- pumps$power * hours_per_year * 30 * electricity_price

total_pump_cost <- pumps$capex + opex_30yr

# ---- LP for pump selection (fixed pump count = 60) ----

pump_constraints <- rbind(

  pumps$head,

  rep(1, nrow(pumps))

)

pump_dirs <- c(">=", "==")

pump_rhs <- c(total_required_head, total_pump_count)


pump_result <- lp("min", total_pump_cost, pump_constraints, pump_dirs, pump_rhs, all.int = TRUE)


if (pump_result$status != 0) stop("Pump optimization failed.")


pump_solution <- pump_result$solution

pump_capex <- sum(pump_solution * pumps$capex)

pump_opex <- sum(pump_solution * opex_30yr)

pump_power <- sum(pump_solution * pumps$power)


# ---- Land pipeline construction options ----

# Methods: A (no limit), B (≤1000 km), C (≤800 km)

land_total_km <- 2645

cost_per_m <- c(1800, 1600, 1400)  # USD/m

cost_per_km <- cost_per_m * 1000


pipe_constraints <- rbind(

  c(1, 1, 1),    # total km = 2645

  c(0, 1, 0),    # B ≤ 1000

  c(0, 0, 1)     # C ≤ 800
```



```
)
pipe_dirs <- c("=", "<=", "<=")
pipe_rhs <- c(2645, 1000, 800)

pipe_result <- lp("min", cost_per_km, pipe_constraints, pipe_dirs, pipe_rhs)

if (pipe_result$status != 0) stop("Pipeline optimization failed.")

pipe_solution <- pipe_result$solution
names(pipe_solution) <- c("km_A", "km_B", "km_C")
land_pipeline_cost <- sum(pipe_solution * cost_per_km)

# ---- Final system costs ----
marine_cost <- 600 * 1000 * 2800
civil_cost <- 12 * 5e6
solar_cost <- 110e6

total_system_cost <- marine_cost + land_pipeline_cost + pump_capex + pump_opex + civil_cost + solar_cost

# ---- Output ----
cat("     Optimized Pump Configuration:\n")
print(setNames(pump_solution, pumps$type))
cat("CAPEX (pumps): USD", format(pump_capex, big.mark=","), "\n")
cat("OPEX (30 yrs): USD", format(round(pump_opex), big.mark=","), "\n")
cat("Total installed pump power:", round(pump_power), "kW\n\n")
cat("     Optimized Land Pipeline Configuration:\n")
print(pipe_solution)
cat("Land pipeline construction cost: USD", format(round(land_pipeline_cost), big.mark=","), "\n\n")

cat("    Final Total System Cost (pipeline + pumps + civil + solar): USD",
    format(round(total_system_cost), big.mark=","), "\n")
```

4. Climate Impact and Failure Risk and 5. Data Visualization and Report Preparation

```
# Load required packages
library(tidyverse)   # For data manipulation and plotting
library(lubridate)   # For handling dates
# Create a sequence of dates for the entire year 2025
dates_glacier <- seq.Date(from = as.Date("2025-01-01"), to = as.Date("2025-12-31"), by = "day")
n_glacier <- length(dates_glacier)
day_of_year <- yday(dates_glacier)

# Simulate daily temperature data using a sine function to mimic seasonal variation
# (simulate a glacier region: low temperatures in winter, high temperatures in summer)
T_mean <- 0        # Mean temperature (°C)
amplitude <- 10    # Temperature amplitude (°C)
phase_shift <- 200 # Phase shift (positions the peak temperature mid-year)
set.seed(123)
```



```
temperature <- T_mean +
  amplitude * sin(2 * pi * (day_of_year - phase_shift) / 365) +
  rnorm(n_glacier, mean = 0, sd = 2)

# Calculate daily glacier meltwater runoff using the degree-day method:
# if temperature > 0°C, then meltwater runoff = degree_day_factor * temperature, otherwise 0
degree_day_factor <- 5  # Unit: mm/(°C·day)
meltwater_runoff <- ifelse(temperature > 0, degree_day_factor * temperature, 0)

# Construct a data frame to store the simulated data
sim_data <- tibble(
  date = dates_glacier,
  day_of_year = day_of_year,
  temperature = temperature,
  meltwater_runoff = meltwater_runoff
)

# Simulate historical runoff data by adding noise to the simulated data
historical_runoff <- meltwater_runoff + rnorm(n_glacier, mean = 0, sd = 3)
historical_runoff <- pmax(historical_runoff, 0)  # Ensure values are not negative
sim_data <- sim_data %>%
  mutate(historical_runoff = historical_runoff)

# (a) Plot the daily glacier meltwater runoff time series
evap_plot <- ggplot(sim_data, aes(x = date)) +
  geom_line(aes(y = meltwater_runoff, color = "Simulated Meltwater"), size = 1) +
  geom_line(aes(y = historical_runoff, color = "Historical Meltwater"),
            linetype = "dashed", size = 1) +
  labs(title = "2025 Glacier Meltwater Runoff Simulation",
       subtitle = "Daily Meltwater Runoff (mm/day)",
       x = "Date",
       y = "Meltwater Runoff (mm/day)",
       color = "Data Source") +
  theme_minimal() +
  theme(
    plot.title = element_text(size = 16, face = "bold"),
    plot.subtitle = element_text(size = 12),
    axis.title = element_text(size = 14),
    axis.text = element_text(size = 12),
    legend.title = element_text(size = 14),
    legend.text = element_text(size = 12)
  )
print(evap_plot)

# (b) Calculate the monthly average glacier meltwater runoff to analyze seasonal variation
monthly_meltwater_summary <- sim_data %>%
  mutate(month = month(date)) %>%
  group_by(month) %>%
  summarise(
    avg_simulated = mean(meltwater_runoff, na.rm = TRUE),
    avg_historical = mean(historical_runoff, na.rm = TRUE)
```



```
  )


# Plot a bar chart comparing monthly average glacier meltwater runoff
monthly_plot <- ggplot(monthly_meltwater_summary, aes(x = factor(month))) +
  geom_bar(aes(y = avg_simulated, fill = "Simulated Data"),
           stat = "identity", position = "dodge") +
  geom_bar(aes(y = avg_historical, fill = "Historical Data"),
           stat = "identity", position = "dodge", alpha = 0.7) +
  labs(title = "Average Monthly Glacier Meltwater Runoff",
       subtitle = "Comparison of Simulated and Historical Data",
       x = "Month",
       y = "Average Runoff (mm/day)",
       fill = "Data Source") +
  theme_minimal() +
  theme(
    plot.title = element_text(size = 16, face = "bold"),
    plot.subtitle = element_text(size = 12),
    axis.title = element_text(size = 14),
    axis.text = element_text(size = 12),
    legend.title = element_text(size = 14),
    legend.text = element_text(size = 12)
  )
print(monthly_plot)

# Define the Penman-Monteith function to calculate potential evapotranspiration (ET0)
penman_monteith <- function(T, RH, u2, Rn) {
  # Calculate saturation vapor pressure (kPa)
  es <- 0.6108 * exp((17.27 * T) / (T + 237.3))
  # Calculate actual vapor pressure (kPa)
  ea <- RH / 100 * es
  # Calculate the slope of the saturation vapor pressure curve (kPa/°C)
  Delta <- 4098 * es / ((T + 237.3)^2)
  # Set the psychrometric constant (kPa/°C)
  gamma <- 0.066
  # Calculate ET0 (mm/day), assuming soil heat flux G = 0
  ET0 <- (0.408 * Delta * Rn + gamma * (900 / (T + 273)) * u2 * (es - ea)) /
    (Delta + gamma * (1 + 0.34 * u2))
  return(ET0)
}


# Simulate weather data for 2025
set.seed(123)
dates_et0 <- seq.Date(from = as.Date("2025-01-01"), to = as.Date("2025-12-31"), by = "day")
weather_data <- tibble(
  date = dates_et0,
  month = month(date),
  # Simulate temperature (°C) based on month: lower in winter, higher in summer
  T = case_when(
    month %in% c(12, 1, 2) ~ rnorm(length(dates_et0), mean = 0, sd = 5),
```

```
  month %in% c(3, 4, 5) ~ rnorm(length(dates_et0), mean = 10, sd = 5),
  month %in% c(6, 7, 8) ~ rnorm(length(dates_et0), mean = 20, sd = 5),
  month %in% c(9, 10, 11) ~ rnorm(length(dates_et0), mean = 10, sd = 5)
 ),
 # Relative Humidity (%)
 RH = runif(length(dates_et0), min = 40, max = 100),
 # Wind speed at 2 meters (m/s)
 u2 = runif(length(dates_et0), min = 1, max = 5),
 # Net radiation (MJ/m²/day): lower in winter, higher in summer
 Rn = case_when(
  month %in% c(12, 1, 2) ~ runif(length(dates_et0), min = 5, max = 10),
  month %in% c(3, 4, 5) ~ runif(length(dates_et0), min = 10, max = 15),
  month %in% c(6, 7, 8) ~ runif(length(dates_et0), min = 15, max = 20),
  month %in% c(9, 10, 11) ~ runif(length(dates_et0), min = 10, max = 15)
 )
)


# Calculate daily ET0 using the Penman-Monteith function
weather_data <- weather_data %>%
 mutate(ET0 = penman_monteith(T, RH, u2, Rn))
print(head(weather_data))


# Plot the daily ET0 time series
evap_plot_et0 <- ggplot(weather_data, aes(x = date, y = ET0)) +
 geom_line(color = "blue", size = 1) +
 labs(title = "2025 Daily Potential Evapotranspiration (ET0) Time Series",
    x = "Date",
    y = "Potential Evapotranspiration (mm/day)") +
 theme_minimal() +
 theme(
  plot.title = element_text(size = 16, face = "bold"),
  axis.title = element_text(size = 14),
  axis.text = element_text(size = 12)
 )
print(evap_plot_et0)


# Summarize average ET0 by month (for seasonal analysis)
monthly_et0_summary <- weather_data %>%
 group_by(month) %>%
 summarise(mean_ET0 = mean(ET0, na.rm = TRUE))


# Plot the monthly average ET0 as a bar chart
monthly_plot_et0 <- ggplot(monthly_et0_summary, aes(x = factor(month), y = mean_ET0)) +
 geom_bar(stat = "identity", fill = "skyblue") +
 labs(title = "Average Monthly Potential Evapotranspiration (ET0) for 2025",
    x = "Month",
    y = "Average ET0 (mm/day)") +
 theme_minimal() +
 theme(
```



```
    plot.title = element_text(size = 16, face = "bold"),
    axis.title = element_text(size = 14),
    axis.text = element_text(size = 12)
  )
print(monthly_plot_et0)



set.seed(123)
dates_risk <- seq.Date(from = as.Date("2025-01-01"), to = as.Date("2025-12-31"), by = "day")
n_risk <- length(dates_risk)

# Simulate risk factors:
# Temperature variability (°C), Corrosion index (0–10), Freeze-thaw cycles (more frequent in winter),
# Extreme rainfall (using a Bernoulli distribution), External stress events (low probability)
temp_variability <- runif(n_risk, min = 5, max = 15)
corrosion_index <- runif(n_risk, min = 0, max = 10)
freeze_thaw <- ifelse(month(dates_risk) %in% c(12, 1, 2),
                      sample(0:3, n_risk, replace = TRUE),
                      sample(0:1, n_risk, replace = TRUE))
rain_prob <- ifelse(month(dates_risk) %in% c(3, 4, 5, 9, 10, 11), 0.2, 0.1)
extreme_rain <- rbinom(n_risk, size = 1, prob = rain_prob)
ext_stress <- rbinom(n_risk, size = 1, prob = 0.05)

# Calculate the comprehensive risk score by assigning different weights to each risk factor
risk_score <- 0.3 * temp_variability +
  0.25 * corrosion_index +
  0.2 * freeze_thaw +
  0.15 * extreme_rain +
  0.1 * ext_stress

# Predict pipeline failure probability using a logistic transformation
predicted_failure_prob <- 1 / (1 + exp(-(-10 + 0.5 * risk_score)))

# Combine the risk data into a tibble
risk_data <- tibble(
  date = dates_risk,
  temp_variability = temp_variability,
  corrosion_index = corrosion_index,
  freeze_thaw = freeze_thaw,
  extreme_rain = extreme_rain,
  ext_stress = ext_stress,
  risk_score = risk_score,
  predicted_failure_prob = predicted_failure_prob
)
print(head(risk_data))

# (a) Plot the daily pipeline risk score time series
risk_plot <- ggplot(risk_data, aes(x = date, y = risk_score)) +
  geom_line(color = "red", size = 1) +
  labs(title = "Daily Pipeline Risk Score",
       x = "Date",
       y = "Risk Score") +
  theme_minimal() +
```



```
  theme(
    plot.title = element_text(size = 16, face = "bold"),
    axis.title = element_text(size = 14),
    axis.text = element_text(size = 12)
  )
print(risk_plot)

# (b) Plot the daily pipeline failure probability time series
failure_prob_plot <- ggplot(risk_data, aes(x = date, y = predicted_failure_prob)) +
  geom_line(color = "blue", size = 1) +
  labs(title = "Daily Pipeline Failure Probability",
       x = "Date",
       y = "Failure Probability") +
  theme_minimal() +
  theme(
    plot.title = element_text(size = 16, face = "bold"),
    axis.title = element_text(size = 14),
    axis.text = element_text(size = 12)
  )
print(failure_prob_plot)

# (c) Summarize risk score and failure probability by month
monthly_risk_summary <- risk_data %>%
  mutate(month = month(date)) %>%
  group_by(month) %>%
  summarise(
    avg_risk = mean(risk_score, na.rm = TRUE),
    avg_failure_prob = mean(predicted_failure_prob, na.rm = TRUE)
  )

# Plot the monthly average pipeline risk score and failure probability (bar chart + line plot)
monthly_plot_risk <- ggplot(monthly_risk_summary, aes(x = factor(month))) +
  geom_bar(aes(y = avg_risk, fill = "Risk Score"), stat = "identity", position = "dodge", alpha = 0.8) +
  geom_line(aes(y = avg_failure_prob * max(avg_risk), group = 1, color = "Failure Probability"), size = 1, linetype = "dashed") +
  scale_y_continuous(
    name = "Average Risk Score",
    sec.axis = sec_axis(~ . / max(monthly_risk_summary$avg_risk), name = "Average Failure Probability")
  ) +
  labs(title = "Monthly Average Pipeline Risk Score and Failure Probability",
       x = "Month",
       fill = "Metric",
       color = "Metric") +
  theme_minimal() +
  theme(
    plot.title = element_text(size = 16, face = "bold"),
    axis.title = element_text(size = 14),
    axis.text = element_text(size = 12),
    legend.position = "bottom"
  )
print(monthly_plot_risk)
```


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From the Yangtze to the Gobi Desert: Designing and Evaluating a Proposed Pipeline for Combatting Desertification

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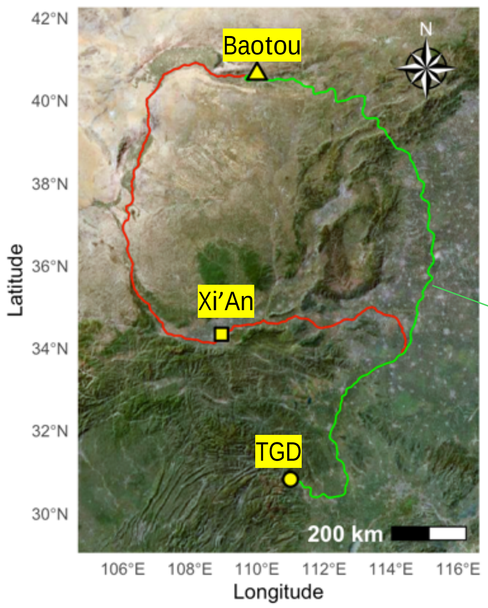
Graphical Abstract

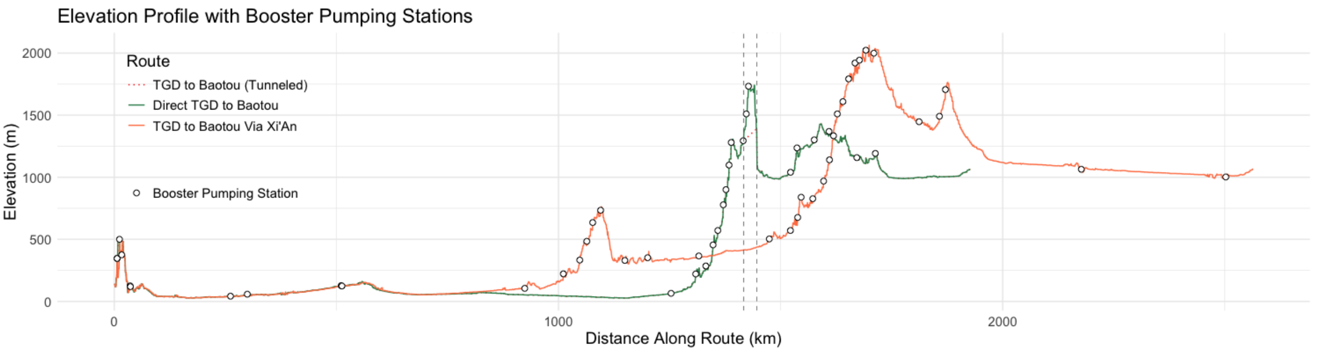


Three pipelines were assessed:

A. Direct route from Three Gorges Dam to Baotou with tunnel
B. Direct route from Three Gorges Dam to Baotou
C. Indirect route via Xi'An

Optimal pipeline (B. Three Gorges Dam to Baotou):

- Nominal diameter: 2000 mm
- Flow: 2 m^3/s
- Length: 1927 km
- Social impact: 400,000,000 lives improved annually
- Environmental impact: 3,600 km^2 p.a. of desertification reversal
- Construction cost: US$ 8 billion
- Lifetime operational cost: US$ 12 billion



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Abstract

This study proposes and evaluates a transregional water pipeline from the Three Gorges Reservoir (TGR) to Baotou at the Gobi Desert's southern edge, aiming to combat desertification in northern China which affects up to 400,000,000 people and costs an estimated US$ 188 billion to China's GDP. Optimal pipeline pathfinding and hydraulic design was conducted for a 2 m diameter pipeline carrying 173 ML/day of water, and booster pumping stations were placed along the route as per head loss requirements. The optimal route was determined to be 1927 km long with 23 booster pumping stations for a power consumption of ~41 MW. Analysis of seasonal precipitation and temperature patterns highlighted concerns about flooding and extreme temperature fluctuations, with central to northern China experiencing temperatures as low as -15 °C in winter and as high as 34 °C in summer. A comprehensive treatment system was designed to ensure resilience against climactic stressors, including large to fine particle filtration, microbial filtration, UV protection, and pH corrosion mitigation strategies. Moreover, by utilizing the hydroelectric and solar energy available along the pipeline route, annual carbon emissions can be reduced by a factor of ten compared to non-renewable energy sources. Tunnelling was considered to minimise energy costs associated with pumping over mountains but was found to be more expensive. The final cost of the Project is estimated to be US$ 20 billion of which US$ 8 billion is the Capital Expenditure and US$ 12 billion is the Operational expenditure.

Keywords: climate resilience, desertification reversal, pipeline design, risk modelling

1. **Introduction/Literature Review**

1.1 Desertification in Northern China

Desertification is land degradation characterised by salinisation, soil erosion, loss of organic matter, depletion of nutrients, and compaction, leading to food insecurity, dust storms, and climate related displacement[1]. It is estimated to cost China 1% of its annual GDP[2] equating to ~US$ 188 billion in 2024[3] and impacts up to 400,000,000 people annually[4,5]. China's ongoing efforts in reverse desertification[6,7] have had a demonstrable improvement[8] including increased vegetation cover, increased biodiversity, and improved soil quality with biocrust formation[9].

Early stages of desertification reversal require significant artificial irrigation (290-340 m^3 water per m^2 of reforested land per year[10]), which, when neglected, results in further groundwater depletion[11].

Degraded land restoration has shown to generate significant socio-economic benefits, ranging from US$ 3 – 6 returns per USD spent over a 30-year period[12].

The Gobi Desert's expansion along the Hexi Corridor has been attributed to groundwater depletion in oasis regions[13] – in some cases directly linked to industrial water users (making up 17.7% of total water consumption in China[14]) such as the Bayan Obo Mine near the city of Baotou which borders the Gobi Desert[15].

1.2 Orographic Water Divide & The Yangtze River

The arid region encompassing the Gobi Desert is bordered by the Dabashan and Qinling Mountain ranges to the south, forming an orographic water divide beyond which are areas of ample precipitation[16].

Below this orographic divide is the Yangtze River – an abundant source of water with an annual mean discharge of approximately 30,000 m^3/s[17].

However, it has a relatively high sediment load and contains significant dissolved nutrients (nitrates & phosphates) and trace elements[17]. The Three Gorges Dam (TGD) impoundment resulted in sediment settling in the Three Gorges Reservoir (TGR) with the trade-off of higher nutrient enrichment[18].

Here, the TGR is considered as a source of water to be transported for desertification reversal.

1.3 Pipeline Megaproject

The Gobi sits on a plateau ~1000 metres higher than TGD, separated also by the Qinling Mountain Range with peaks some 3000 m above sea level. Gravity based water transport (by means of pipeline or aqueduct) are therefore impossible. The difficult terrain also provides significant challenges with road and rail transportation.

This project assumes a high-pressure water pipeline as a design basis. The straight-line distance between Baotou and the TGR is 1100km – among the longest pipelines in operation as of 2025[19]. Furthermore, the Yangtze's water quality regarding nutrient enrichment and pH issues requires specific infrastructure design nuances regarding material selection and water treatment [18].

Moreover, the pipeline design must address various climate challenges along its route from central to northern China. Factors such as, temperature extremities and fluctuations, flooding, and seismic activity must all be accounted for to ensure the operational reliability, structural integrity, and long-term longevity of the pipeline.

2. **Methodology**

2.1 Assumptions

Pipeline design criteria are summarised in Table 1.

Table 1: Summary of Pipeline Design Criteria.

Variable	Assumption	Justification	Reference
Water Source	TGD / TGR	Lowest sediment levels in the Yangtze[18].	Section 1.1
Water Sink	Baotou	Major population centre bordering the Gobi Desert with a large industrial base[15].	Section 1.1
Design Life	50 years	Expected pay-off period of 30 years[20].	Appendix
Flow Rate	2 m^3/s	Calculated based on desertification rate and Baotou water demand.	Appendix

2.2 Pathfinding Methodology

Pipeline routing, plots, and calculations were performed using R via R Studio. An R script for pathfinding was developed to use the NASA ACE2 Digital Elevation Model (DEM)[21].
R code philosophy was as follows:

1. Route start and end latitude / longitude co-ordinates were defined.
2. A bounding box was defined larger than the start and end co-ordinates. The DEM was only processed in this bounding box.
3. A cost matrix was generated for the bounding box using the equivalent ratio (k) between static head (elevation) and frictional pressure drop over pipe length (Pythagorean distance).
4. Path was computed and exported as a path file (.GPX) for processing.
5. Path distance, cumulative elevation gain, total elevation gain, frictional and static pressure drops were computed in a separate script.
6. Tunnels were computed by manually selecting tunnel start and end points and manually modifying the route path. **NOTE**: route files typically overlay a 2D route over a known elevation model. As such, the tunnels are unable to be computed directly in the pathfinding script.

2.3 Booster Pumping Station Placement

Booster pumping stations were placed along the pipeline to ensure the total head loss between stations does not exceed the allowable pump head capacity.
At each segment along the route, the cumulative head loss h_loss is computed as the sum of frictional and elevation-induced losses:

$$h_{loss} = \Sigma [(P_{friction} + P_{elevation}) / (\rho * g)]$$

Where $P_{friction}$is the pressure drop due to friction, $P_{elevation}$ is the pressure required to overcome elevation gain, ρ is the fluid density (1000 kg/m^3), and g is gravitational acceleration (9.81 m/s^2).
A new pumping station is inserted whenever h_loss ≥ H_max, where H_max is the maximum allowable pump head (160 m). After each station placement, the cumulative loss counter is reset.

2.4 Pathfinding Cost Function

To develop a factor (k) for the pathfinding cost function along a pipe on a 45° slope:

$$\Delta P_f = f \cdot \frac{L}{D} \cdot \frac{\rho v^2}{2}$$

$$\Delta P_s = \rho g \Delta z = \rho g L \cdot \sin(45°)$$

Where ΔP_f is frictional pressure drop, $f$is the friction factor, L is the equivalent length of pipe, D is the diameter, and ΔP_s is the static pressure drop.
The ratio then becomes:

$$\frac{\Delta P_f}{\Delta P_s} = \frac{f v^2}{g D^2}$$

With f = 0.01,v = 0.6366 m/s,D = 2 m,g = 9.81:

$$k = \frac{\Delta P_f}{\Delta P_s} \approx 0.00015$$

2.5 Pumping Station Design & Placement

The selected pumps were inline centrifugal water pumps with a maximum head of 160 m and a maximum flow rate of 2400 m^3/h[22] – 3 pumps were required for the pipeline design flow of 2 m^3/s.

Each pump was designed to be independently isolated for automatic switchover and have a check valve on the outlet to prevent backflow in steep sections of pipe.
Variable speed drives (VSD) were selected to allow for slow pump ramp ups on startup and a lower minimum flow than continuous speed drives.
Full redundancy was selected to allow for greater uptime; therefore, each pumping station contains 6 pumps in a 6x33% redundant configuration (Figure 1).
Pressure – vacuum relief valves (P-VRV) were implemented on pump suction to mitigate against high- and low-pressure surges upstream of the pumping station.
Pressure relief valves (PRV) were placed on the pump discharge line to protect the pipeline infrastructure from a pressure excursion.
Bypass flow control was selected to allow for a lower minimum flow delivery[23] (as per fluctuating irrigation demands).

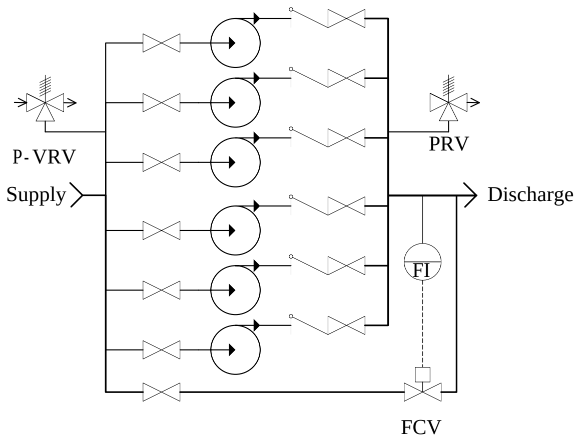

Figure 1: Preliminary booster pumping station design indicating 6x33% redundancy and bypass flow control. Pressure – vacuum relief valves on pump suction, pressure relief on pump discharge.

Booster pumping stations were also determined to include a pipeline isolation valve on the higher-elevation side to allow for maintenance with minimal water losses.
This booster pumping station design is compact and may be housed in prefabricated structures (such as within shipping containers) for rapid on-site installation.
The net booster pumping station cost was estimated to be US$ 1,045,000 as seen in Table 2.
Pumping stations were placed along the pipeline where cumulative hydraulic head loss exceeded the maximum allowable pump head of 160 m. Head loss (H_{loss}) was computed as the sum of frictional and elevation-induced losses:

$$H_{loss} = H_{friction} + H_{elevation}$$

Frictional pressure drop was calculated using the Darcy-Weisbach equation:

$$H_{friction} = f \cdot \left(\frac{L}{D}\right) \cdot \left(\frac{v^2}{2g}\right)$$

Where f is the Darcy friction factor, L is pipe length, D is diameter, v is flow velocity, and g is gravitational acceleration. Friction factor f was determined using the Colebrook equation for turbulent flow:

$$\frac{1}{\sqrt{f}} = -2\, log10\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right)$$

Were ε was assumed to be 0.015 mm for GFRP[22].
Static head was calculated as:

$$H_{elevation} = max(\Delta z\,,\ 0)$$

Where Δz is the change in elevation over distance L. A pumping station was inserted whenever:

$$H_{loss} \geq H_{pump,max}$$

With $H_{pump,max}$ of 160 m per the chosen pump. This was an iterative calculation where cumulative losses were reset after each pumping station.

Table 2: Booster pumping station cost estimation.

Item	Unit Cost (US$)	Qty	Total Cost (US$)
Pump	30,000[24]	6	180,000
Pump isolation valves (DN650)	30,000	12	360,000
P-VRV	20,000[25]	1	20,000
VRV	10,000[25]	1	10,000
FI	15,000[26]	1	15,000
FCV (DN2000)	200,000[25]	1	200,000
Pipeline isolation valve (DN2000)	200,000[25]	1	200,000
Instrumentation & controls	20,000[23]	1	20,000
Building infrastructure	40,000	1	40,000

2.6 Risk modelling

2.6.1 Earthquakes

Sections of the pipeline crossing the mountain range between Hebei and Shanxi Prefectures crossed an area of high earthquake occurrence. As such it was important to estimate the probability of earthquakes occurring in the area which could affect the pipeline.

The Gutenberg-Righter Relationship can be written as:

$$\log\left(N\left(M\right)\right) = a - b * M \qquad (1)$$

Where N(M) describes the number of earthquakes of magnitude M or larger in a year and a, b being constant values determined by historical data for an area[27].
By determining the a and b constants for a small area using historical earthquake data, we can calculate the likelihood of earthquakes of a significant magnitude or higher or express that as a number of years on average before the next earthquake.

2.6.2 Pipe failure

Pipeline failure was modelled using a cumulative distribution function based on a failure rate adjusted by the length of the pipe as in equation (X):

$$F(t) = 1 - e^{\lambda L t} \qquad (X)$$

Where λ is the failure rate in failures per year per kilometre, L is the pipe length in km and t is the time period in years. The time for maintenance could be calculated by assigning a threshold value of 0.95 for F(t) and determining the value of t, indicating the time interval before which the pipeline has a 5% chance of experiencing a rupture or break.

2.7 Method Limitations

1. NASA's DEM data is at a high spatial resolution (2.5 arcminutes[21]) and therefore requires some level of compression to optimise processing time.
2. R code runs on a single processor core with a high memory demand. Initial pathfinding runs took ~240 minutes to complete, this was progressively optimised down to ~3 minutes. It was also observed that computation was ~150-200% faster on an ARM CPU versus x86 architecture.
3. Bounding box was manually set based on elevation plots. Increasing bounding box size increased compute times exponentially. It was assumed that the optimal route would not extend beyond this bounding box. This is a reasonable assumption but may result in inconsistencies if repeated with larger bounding boxes.
4. Pathfinding cost function only accounted for distance and elevation. It was thus geographically agnostic, and the resultant path frequently cut through bodies of water and population centres. This was accepted as a reasonable error of a path of these lengths in a preliminary study stage. Further optimisation could be performed using land usage data[20] to avoid existing developments, as well as including multi-hazard maps which include seismic, climactic, and wildfire risk.
5. Modelling of risk is inherently probabilistic based on past data and testing and should appropriately be accounted for in the expectation of repair and maintenance.

3. Results and Discussion

3.1 Pipeline Routing

Two main routes with further sub-paths were chosen for comparison:

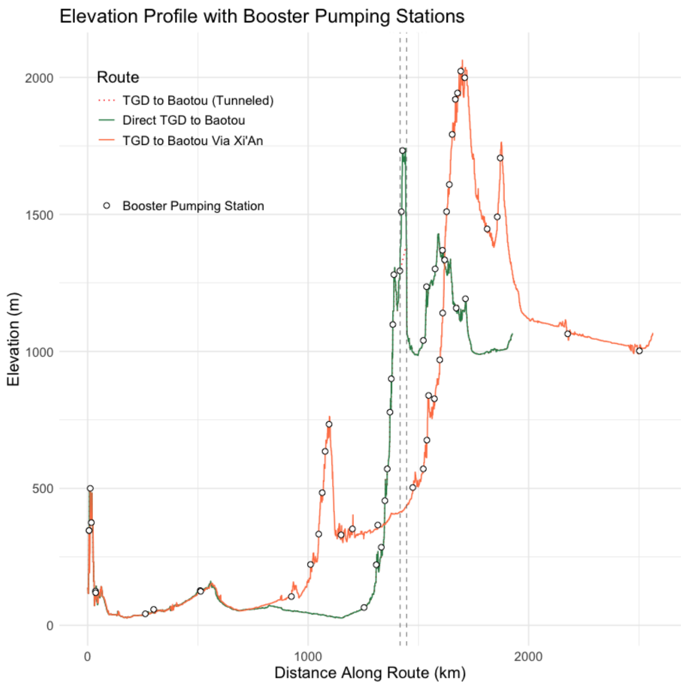

Figure 2:Change in frictional and elevational pressure drops along the pipeline.

1. Direct route: optimal path between the TGD and Baotou. This was further divided into:
   a. Direct route.
   b. Direct route with a tunnel across the highest peak.
2. Indirect route: TGD to Xi'An to Baotou. This aimed to determine whether the benefits of crossing the orographic divide early outweighed cost factors associated with suboptimal routing.

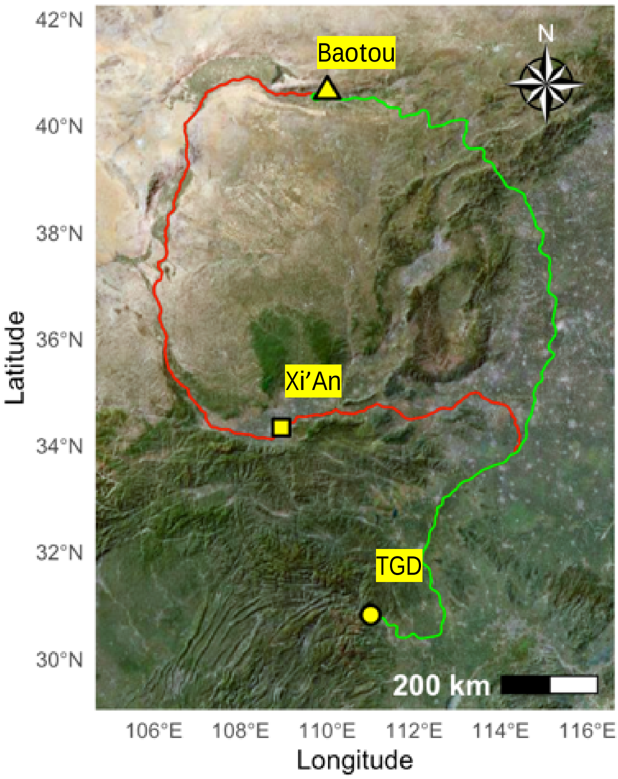

Figure 3: Proposed pipeline paths between TGD and Baotou. Direct route (green) and indirect route (red)

Route	Distance (km)	Total Elevation Gain (m)	Net Elevation Gain (m)	No. of booster pumping stations	Pumping station cost ($ US)	Operational cost ($ US p.a.)	Pumping power requirement (MW)
Direct route	1926	4359	1714	23	24,000,000	TBD	41

3.2 Hydraulic Modelling

Frictional pressure drop is proportional to pipeline length while static head is proportional to elevation gain.

Figure 2 indicates booster pumping station placement along each route based on the calculated pipeline length and elevation profiles.

The optimal route per pathfinding characteristics requires 23 booster pumping stations, while the indirect route via Xi'An requires 34 as per Table 3.

Inclusion of a tunnel reduces the length and therefore reduces the required pumping stations by 1 (22 required in total). A tunnel also reduces the pumping power requirement by 8 MW

Table 3: Comparison table between the chosen routes

(~20% decrease).

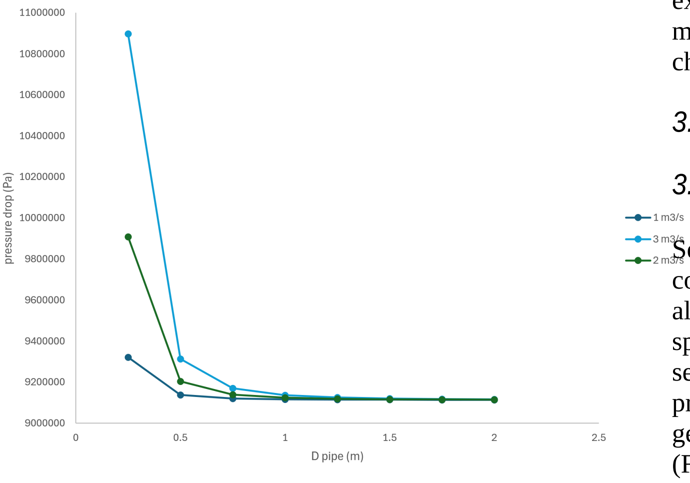

Figure 4: comparison of Pressure drops along the pipeline for varying flow rates and pipe diameters

Figure 4 demonstrates that across a range of acceptable volumetric flow rates of water, pipes of diameter 1 m or greater exhibit little difference in pressure drop while more constricted piping both always produces a larger pressure drop due to increased flow velocities but is also more greatly affected by changes in flow rate. A pipe width of 1 m corresponds to flow velocities of 1.3-4 m/s for flow rates 1-3 m^3/s which is an adequate agreement with common flow heuristics [28] for water transport.

Direct route with tunnel	1898	3942	1402	22	23,000,000	TBD	33
Indirect Route	2583	5391	2396	34	35,500,000	TBD	48

3.3 Consideration of tunnelling

Along the direct route between the Three Gorges Dam and Baotou there is a potential benefit to implementing a tunnel through a large mountain range to reduce energy expenditure on pumping associated with elevation increases. The rock type in this area has been identified as igneous rocks such as granite, dolerite and porphyry[29] which is difficult to bore through [30] indicating an increased CAPEX cost at the benefit of a reduced OPEX. Given the increased frequency of earthquakes in the area discussed section 3.4, the presence of 'harder' rock types does have the benefit of increased seismic activity resistance.

Projects have been completed to produce large tunnels through igneous terrain previously such as the Gotthard Base railway tunnel running through central Europe at a length of 85 km and cost of US$ 12 billion. At a similar rate it could be expected that a tunnel here would cost at a maximum US$ 6 billion for 40 km, but potentially cheaper due to Chinese labour values[31].

3.4 Climactic Risks and Impacts

3.4.1 Seasonal Water and Temperature Variation

Seasonal weather variations and region-specific conditions present a range of design challenges along the pipeline. For instance, the precipitation spikes engendered by the East Asian monsoon season must be accounted for, whereby the mean precipitation exceeds 100 mm per month in the general area between the TGD and Baotou (Figure. S1). Flooding is an issue for all geographical regions along the pipeline, with the Baotou area being more susceptible to intense flash flooding[32]. This induces the rise of hydrotechnical hazards including watercourse erosion, landslides, and vortex shedding[33]. These hazards are especially significant, as the proposed pipeline will be predominantly above ground. Not only can watercourse erosion and landslides undermine pipeline foundations, but they can also significantly increase turbidity which introduces an array of sediments to the intake water. Accordingly, water quality is reduced and internal stress increased. Moreover, there will be a surge in microbe quantity subsequent to flooding, in turn increasing the risk of corrosion and biofouling[34].

Considering the significant temperature variations throughout the year in China is imperative for optimal pipe design. Thermal expansion and contraction are inevitable due to the sizeable ambient temperature disparity between the summer season (> 30 ℃) and winter season (< -15 ℃) (Figure. S1). These repeated fluctuations can lead to cyclic fatigue, due to varying tensile and compressive stresses[35]. Additionally, regions near the TGD have a humid subtropical climate and experience the highest temperatures along the pipeline route (Figure. S2). Moisture, in tandem with high heat, exacerbates corrosion and promotes microbial growth. In addition, prolonged exposure to UV radiation can degrade not only coatings, but also the molecular chains in plastic pipes, resulting in embrittlement[36]. Conversely, geographical areas near Baotou reach temperatures well below freezing point (Figure. S2). When pipeline wall temperature is below freezing, ice formation on the inner surface could occur due to the heat temperature between the cold pipe and water. This can potentially cause problematic blockages, increase pressure drop, and reduce flow capacity[37].

3.4.2 Impacts on Pipeline Design

Filtration

A comprehensive filtration system is needed to mitigate the sedimentation impacts and to prevent risks from contamination. The pipeline filtration system should include the following:
Prefiltration: This initial stage is essential for the removal of larger particulate matter immediately following points. This is particularly crucial after extreme flooding events, where larger objects and particulate matter are displaced. Coarse bar screens made of stainless steel with spacings of 25 mm should be complemented by fine bar screens with spacings of 5 mm to capture large debris such as rags, branches, and plastics[38]. Additionally, hydrocyclones should also be positioned near intake points for further retention of suspended particles. Centrifugal force is utilised to remove particles (sand, silt, and other debris) to protect finer downstream filtration systems from potential damage and improve system efficiency[39]. Flocculation and settling basins will then be used to agglomerate and remove finer particles that remain post-cyclonic separation[40].
Secondary Filtration: This stage targets the removal of residual harmful particles and contaminants that have evaded primary treatment. The filtration units will be situated at intermediate stations, as well as near both intake and endpoint locations along the pipeline. This will ensure comprehensive contaminant removal throughout the pipeline network. Rapid sand filtration is employed to capture fine particles as small as 5 microns and is able to manage the specified flow rate of 2 m^3/s[41]. Additionally, activated carbon filtration is integrated to adsorb organic compounds, while ultrafiltration is utilized to eliminate microbial contaminants. This multifaceted approach is particularly crucial in humid regions (near the source) and in areas prone to extreme flooding, where the risk of organic matter accumulation and microbial proliferation is elevated. Subsequently, UV sterilisers will be used, as they are able to harness UV-C light to inactivate any remaining microorganisms by damaging their DNA[42].
Please note that further water clarification for uses such as consumption will be carried out at the site location.

Insulation and Coatings

To mitigate the harmful effects of the varying temperature conditions along the pipeline route, a segmented insulation strategy will be implemented. This will ensure that suitable insulation materials are chosen based on the specific thermal demands of disparate geographic areas, thereby optimising longevity and performance. In regions near Baotou subject to extremely cold winters, polyurethane foam will be used to prevent freezing due to its low thermal conductivity (~0.02 W/m·K) and ability to maintain its mechanical strength at subzero temperatures. This in turn minimises heat transfer, effectively enhancing energy efficiency and reducing operational costs[43]. However, polyurethane foam is susceptible to thermal degradation in higher temperatures, making it an unsuitable material for hotter climates. Conversely, for pipeline segments near the TGD and Central China with hotter summers and high humidity, calcium silicate insulation will be utilised. Calcium silicate high thermal stability and resistance to moisture absorption, making it ideal for subtropical climates. Furthermore, its robust structure prevents material breakdown under prolonged heat exposure, ensuring system reliability and long-term insulation efficiency.
Moreover, UV-resistant epoxy resin coatings will provide protection against solar radiation induced damage, corrosion, and chemical damage[44]. This should be applied in conjunction with a silver derived antimicrobial coating containing > 2000

mg/L silver zeolite to prevent the formation of a biofilm and impede biodeterioration[45].

Glass Fiber Reinforced Polymer piping (GFRP) is sensitive to both alkaline and acidic conditions. To monitor changes in water pH resulting from previously mentioned biomass and nutrient enrichment in the TGR, pH sensors should be installed near the intake points. The UV-resistant epoxy resin will act as a protective barrier to mitigate pH corrosion. Additionally, automated dosing systems will be implemented to release citric acid or calcium hydroxide when needed based on real time monitoring from the pH sensors.

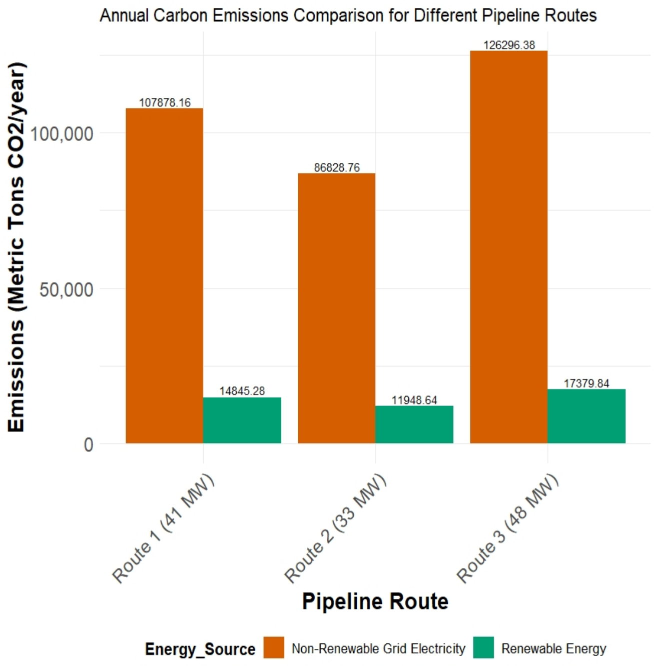

Figure 5. Carbon emissions produced for each pipeline route using non-renewable or renewable energy sources. Data was collected from the Australian Energy Market Operator[48].

Treatment Cost

Table 4. CAPEX and OPEX for filtration components, insulation materials, coating materials, and sensors.

	CAPEX (US$)	OPEX (US$/year)
Cost	15,000,000	1,700,000

The CAPEX and OPEX for the pipeline treatment system was calculated using published market values and established industry estimates. It was assumed that 22 units of coarse board screens, hydrocyclones, activated carbon, and UV-C sterilisers will be implemented at intake and outlet points, as well as near pumping stations. Furthermore, 2 units of settling basins and flocculation tanks was accounted for in the estimation[46,47].

3.4.3 Pipeline Sustainability

The pipeline location offers significant geographical advantages that can be harnessed for energy. Notably, the hydroelectric energy generated by the TGD and the abundant solar potential enable a substantial reduction in the operational carbon emissions of the pipeline, compared to the scenario where non-renewable energy sources are used (Figure 5).

3.5 Cost and Energy Optimisation

3.5.1 Pipeline CAPEX Estimation

Pipeline material cost was extrapolated using a standard HDPE piping chart from 32-800 mm diameter[49], resulting in an estimated cost of approximately US$ 760,000/km. Three CAPEX sheets were created for each proposed route: Route A: Tunnel option, Route B: Direct pumping over the mountain and Route C: Indirect route around terrain. A scaling factor of 1.5 was applied to the pipeline material cost to account for fittings, valves, and monitoring systems[50]. Additionally, the CAPEX for pumping stations was determined using data from Table 3. Construction costs were estimated at US$ 1.3 million/km, again based on pipeline length[50]. Extra construction costs were factored in for elevation and terrain access on the non-tunnel routes[51]. Tunnel construction was estimated at US$ 6 billion. A contingency of 10% was added to the final CAPEX figures.

3.5.2 Energy Optimisation and OPEX Analysis

Power supply was assumed to come from a mix of hydro and solar, both readily available along the pipeline route. It was assumed that a third of the pumping power demand would be met by the Three Gorges Hydroelectric Plant, the remaining two thirds would come from various solar farms positioned along the pipeline.

Purchasing energy from existing providers was determined to be more cost-effective than investing in proprietary generation infrastructure. However, battery systems were still considered essential for grid interruptions and remote operation. These were sized to provide 8 hours of backup supply. Lithium-ion battery costs in China were found to be US$ 88/kWh[52], and total battery costs were calculated per route based on specific energy requirements. Energy purchasing prices were: $ 42/MWh for hydro[53] and $ 49/MWh for solar[54]. With year-round operation assumed, the pipeline would require 8,760 MWh annually. Energy costs were thus calculated based on the pumping power requirement per route. Other OPEX considerations included maintenance: estimated at US$ 5,000/km annually[55], labour: assumed to be 2% of total pipeline cost, insurance: priced at 5% of the insured sum (total CAPEX), amortised over 50 years at a 3% annual interest rate[56] and environmental monitoring: assumed to be 40% of maintenance cost

3.5.3 Final Costing

Table 5. below shows the total cost for each route option based on both CAPEX and OPEX over a 50-year period. The results highlight that while the tunnelling route (Route A) saves on OPEX, its US$ 6 billion initial investment is a significant disadvantage. In contrast, the pumping route over the mountain (Route B) proves to be more cost-effective, despite its operational costs. Furthermore, potential risks associated with the tunnel, such as tunnel cave-ins and the high cost of repairs, also add a level of failure risk that must be considered when evaluating the long-term feasibility of the tunnel option.

Table 5. Total costs of each proposed route

Metric	Value (Billion US$)	Total Cost (Billion US$)
Total CAPEX (Option A)	13	23
Total OPEX (Option A)	10	
Total CAPEX (Option B)	8	20
Total OPEX (Option B)	12	
Total CAPEX (Option C)	11	27
Total OPEX (Option C)	16	

3.6 Failure Risk analysis

A large number of operational, financial and social risks are present in the construction and operation of the pipeline, including but not limited to: degradation of piping, joints, pumps and other structural elements; damage from natural disasters; errors in operation; costing overshoots and unexpected repair work; and impact on local communities.

In this section, a portion of the direct route pipeline covering the highest altitude section is analysed for several risk factors to provide insight into the risk considerations for a project of this size with further analysis left to later publication: damage and disruption from earthquakes as well as the financial risks of constructing a tunnel through the section.
Additionally, pipe failure is considered to determine maintenance scheduling requirements

Using the Gutenberg-Richter relationship to analyse the rough area over which the pipeline passes (bounded by latitudes 38-40 and longitudes 110-115) revealed that the average number of years before an earthquake of magnitude 4 or higher occurred affecting a given point was 42 years. Considering a project lifespan of 50 years, this is a significant frequency of earthquakes in the region. To mitigate the effects of earthquakes, Polyethylene or polymer piping such as Glass Fibre Reinforced Polymer (GFRP) should be used as it was found to be resistant to seismic activity in New Zealand[57], however a focus on fast repair responses should also be used as it is often impossible to design out the effects of an earthquake. Estimates for repairs to water pipelines damaged by seismic activity have been modelled to be in the range of US$ 10-20 million for lengths of 2.85 km pipe sections[58].

This location has also been identified as an optimal location for a tunnel given that there is an otherwise large increase and decrease in elevation that would require additional pumping power to overcome. Constructing a tunnel in this location poses a financial risk as it is a structure more prone to damage by an earthquake compared to a surface pipeline. As such in the evaluation of the cost effectiveness of the implementation of a tunnel, the cost to fix a collapsed tunnel is an important factor in the event of a serious earthquake. Extrapolating from historic costing for tunnel repairs (US$ 70 million to repair 2km of tunnel in the US[59]), a repair cost could be expected to be up to US$ 1.4 billion to repair the entire 40km length of tunnel, although the event that the entire tunnel would be that heavily damaged is unlikely to occur so as such a US$ 70 million cost of repair is more realistic and a reasonable cost for a low likelihood event.

Pipe failure is an important failure risk to consider as it can occur at any point on the pipeline and requires constant monitoring and frequent maintenance. There was very little available literature on the failure rate of GFRP however given the operating conditions not being high pressure, the failure rate of steel pipe was used instead as 0.00029 failures/yr/km [60]. Applying this calculation over the entire direct route yielded a maintenance schedule of every 1.1 months. This value is a reasonable repair and maintenance schedule and could be further expanded by the implementation of sensors to ensure efficient monitoring, maintenance, and safety. These include flow and pressure monitoring devices like electromagnetic and ultrasonic flow meters, which measure water flow without obstructing the pipeline, as well as pressure transmitters and differential pressure sensors that detect leaks or blockages[61].
Leak detection is critical, utilizing acoustic leak detectors, hydrocarbon/water-sensing fibre optic cables, and ground-penetrating radar (GPR) to identify potential failures without excavation. Structural integrity is monitored through strain gauges, distributed temperature sensors (DTS), and corrosion sensors, which help assess material stress, temperature variations, and corrosion risks [62].
Water quality is maintained using turbidity, pH, dissolved oxygen, and total organic carbon (TOC) sensors to detect contamination[63]. Additionally, remote sensing systems such as SCADA, satellite and IoT connectivity, and drone-based infrared imaging enable real-time monitoring, particularly in remote desert environments[63,64]. Given the harsh conditions of the Gobi Desert, these systems prioritize durability, remote connectivity, and energy efficiency, and could incorporate solar-powered sensors.

4. Conclusion

Three water pipeline routes were considered for the purpose of delivering 172.8 ML of water per day from the Three Gorges Reservoir to the city of Baotou in Northern China for use in combatting desertification as well as industrial uses. The results of this article were compiled in the decision matrix in appendix 1, resulting in the direct route without a tunnel being the optimal route. The Direct route without tunnel provides the greatest benefit in terms of construction and operational efficiency at a predicted cost of US$ 20 Billion across a 50 year lifespan. The route spans 1927 km running east of the Qinling mountain range before passing over the mountain range towards Baotou. Considerations of the varying climatic conditions across the route were made and it was found that thermal insulation for heat and cold protection were required to the sum of US$ 1.2 million and an annual cost of water treatment of US$ 15 million with an initial construction cost of US$ 1.7 million. Tunnelling was considered in the construction to minimise operational cost associated with pumping over mountains, however the CAPEX requirements were too large to justify this decision with the route costing a predicted additional US$ 3 billion. Risk factors associated with earthquakes and pipe failure were considered as examples of design considerations for the construction of this project with further risk factors for later publications.

Further research and modelling of this pipeline project should aim to quantify additional risk and profile stakeholders in the project such as industrial companies, farmers and citizens living along the pipeline to determine their stakeholder requirements.

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Attributions

Graphical Abstract: Osama Rehman
Introduction: Osama Rehman
Pathfinding: Osama Rehman
Hydraulic Modelling: Osama Rehman and Matthew Wolfenden
Risk Modelling: Matthew Wolfenden
Climate analysis: Karinna Yee
Cost and energy optimisation: Jonathan Tapia

Other sections were worked on communally

References

1. Kassas, M. Desertification: a general review. *J Arid Environ* **30**, 115–128 (1995).

2. Cheng, L. *et al.* Estimation of the Costs of Desertification in China: A Critical Review. *Land Degrad Dev* **29**, 975–983 (2018).

3. China achieves 2024 growth target, bolsters global economy. https://english.www.gov.cn/news/202501/18/content_WS678ae501c6d0868f4e8eeef7.html.

4. How communities in China helped keep desertification at bay – DESERTIFICATION. https://desertification.wordpress.com/2019/09/06/how-communities-in-china-helped-keep-desertification-at-bay/.

5. China's 'Great Green Wall' Fights Expanding Gobi Desert. https://www.nationalgeographic.com/science/article/china-great-green-wall-gobi-tengger-desertification.

6. Lyu, Y. *et al.* Desertification Control Practices in China. *Sustainability 2020, Vol. 12, Page 3258* **12**, 3258 (2020).

7. China completes 3,000-km green belt around its biggest desert, state media says | Reuters. https://www.reuters.com/world/china/china-completes-3000-km-green-belt-around-its-biggest-desert-state-media-says-2024-11-29/.

8. Wang, X., Chen, F., Hasi, E. & Li, J. Desertification in China: An assessment. *Earth Sci Rev* **88**, 188–206 (2008).

9. World Bank Group. Halting Desertification in China. https://www.worldbank.org/en/results/2021/07/26/halting-desertification-in-china (2021).

10. Sun, S., Xiang, W., Ouyang, S., Hu, Y. & Peng, C. Balancing Water Yield and Water Use Efficiency Between Planted and Natural Forests: A Global Analysis. *Glob Chang Biol* **30**, (2024).

11. Lu, C., Zhao, T., Shi, X. & Cao, S. Ecological restoration by afforestation may increase groundwater depth and create potentially large ecological and water opportunity costs in arid and semiarid China. *J Clean Prod* **176**, 1213–1222 (2018).

12. Nkonya, E., Mirzabaev, A. & von Braun, J. Economics of land degradation and improvement - A global assessment for sustainable development. *Economics of Land Degradation and Improvement - A Global Assessment for Sustainable Development* 1–686 (2015) doi:10.1007/978-3-319-19168-3/COVER.

13. Zhu, B. Q., Zhang, J. X. & Sun, C. Potential links of gobi, dust, and desertification: A comprehensive understanding from aeolian landform evolution in a middle-latitude desert. *Sediment Geol* **428**, 106049 (2022).

14. Ministry of Water Resources. *Implementing Water-Related Goals of the United Nations 2030 Agenda For Sustainable Development Chapter 3*. (2023).

15. Wang, Q. Q. *et al.* Water Conservation and Ecological Water Requirement Prediction of Mining Area in Arid Region Based on RS-GIS and InVEST: A Case Study of Bayan Obo Mine in Baotou, China. *Sustainability (Switzerland)* **15**, 4238 (2023).

16. Zeng, X. *et al.* Drainage-divide migration at the Qinling and its implications for the drainage reorganization and rift evolution of the Weihe graben, Central China. *Geomorphology* **475**, 109658 (2025).

17. Zhu, Z. N. *et al.* Monitoring of Yangtze River Discharge at Datong Hydrometric Station Using Acoustic Tomography Technology. *Front Earth Sci (Lausanne)* **9**, 723123 (2021).

18. Li, Z. *et al.* Water quality trends in the Three Gorges Reservoir region before and after impoundment (1992–2016). *Ecohydrology & Hydrobiology* **19**, 317–327 (2019).

19. Bruschi, R. From the Longest to the Deepest Pipelines. Preprint at https://dx.doi.org/ (2012).

20. Global Urban Footprint. https://www.dlr.de/en/eoc/research-transfer/projects-missions/global-urban-footprint.

21. Berry, P. A. M., Smith, R. G. & Benveniste, J. ACE2: The New Global Digital Elevation Model. *International Association of Geodesy Symposia* **135**, 231–237 (2010).

22. Inline Centrifugal Water Pump Manufacturers, Factory Price - JUSHI PUMP. https://www.jushipump.com/product/horizontal-chemical-process-pipeline-inline-centrifugal-water-pump/.

23. DEE, G. M. Jones. & Robert L. Sanks, P. PE. Pumping Station Design. (2011).

24. DELIVERING PUMPING SOLUTIONS 2020 PRICE LIST.

25. FLOMATIC Valves 2025 Price List. https://www.flomatic.com/wp-content/uploads/2025/02/Price-List-2025.pdf.

26. SITRANS FS230 - Siemens Global. https://www.siemens.com/global/en/products/automation/process-instrumentation/flow-measurement/ultrasonic/clamp-on/sitrans-fs230.html.

27. Southern California Earthquake Center. Gutenberg-Richter Relationship.

28. Couper, J. R., Penney, W. R., Fair, J. R. & Walas, S. M. Rules of Thumb: Summary. *Chemical Process Equipment* xiii–xx (2012) doi:10.1016/B978-0-12-396959-0.00031-8.

29. Li, Z. *et al.* Age and petrogenesis of ore-bearing porphyry from the Houyu Mo-polymetallic deposit, central North China Craton. *Ore Geol Rev* **169**, (2024).

30. Xu, H., Geng, Q., Sun, Z. & Qi, Z. Full-scale granite cutting experiments using tunnel boring machine disc cutters at different free-face conditions. *Tunnelling and Underground Space Technology* **108**, 103719 (2021).

31. Associated Press. After 17 years and $12 billion, Switzerland inaugurates world's longest rail tunnel. *Los Angeles Times* (2016).

32. China floods: The families torn apart by 'huge, furious waves'. https://www.bbc.com/news/world-asia-china-66458546.

33. Dooley, C., Prestie, Z., Ferris, G., Fitch, M. & Zhang, H. Approaches for evaluating the vulnerability of pipelines at water crossings. *Proceedings of the Biennial International Pipeline Conference, IPC* **2**, (2014).

34. Dzodzomenyo, M., Asamoah, M., Li, C., Kichana, E. & Wright, J. Impact of flooding on microbiological contamination of domestic water sources: a longitudinal study in northern Ghana. *Appl Water Sci* **12**, 1–10 (2022).

35. PIPA POP010A-Part 1-Polyethylene Pressure Pipes Design for Dynamic Stresses-Issue Part 1: Polyethylene Pressure Pipes Design for Dynamic Stresses.

36. Pipe Institute, P. TR-18/2019. (2019).

37. Kitanin, L., Smirnov, Y. A. & Lebedev, M. E. Development of Flow and Heat Transfer During Filling a Pipeline with Water at the Pipe Wall Temperature Below the Freezing Point. *Journal of Engineering Physics and Thermophysics* **89**, 808–814 (2016).

38. Bar Screen In Wastewater Treatment - Water & Wastewater. https://www.waterandwastewater.com/bar-screen-in-wastewater-treatment/.

39. Soccol, O. J. & Botrel, T. A. Hidrociclone para pré-filtragem da água de irrigação. *Sci Agric* **61**, 134–140 (2004).

40. Terry, B. L. COAGULATION, FLOCCULATION AND CLARIFICATION OF DRINKING WATER Engelhardt, Application Development Manager, Drinking Water. (2014).

41. Rapid Sand Filtration: Efficient Water Treatment Method - Water & Wastewater. https://www.waterandwastewater.com/rapid-sand-filtration-efficient-water-treatment-method/.

42. Chen, J. *et al.* Self-powered antifouling UVC pipeline sterilizer driven by the discharge stimuli based on the modified freestanding rotary triboelectric nanogenerator. *Nano Energy* **95**, 106969 (2022).

43. Physical properties of polyurethane insulation Safe and sustainable construction with polymers.

44. Tuominen, O., Tuominen, E., Vainio, M., Ruuska, T. & Vinha, J. Thermal and moisture properties of calcium silicate insulation boards. *MATEC Web of Conferences* **282**, 02065 (2019).

45. Vela-Cano, M., Garcia-Fontana, C., Osorio, F., González-Martinez, A. & González-López, J. Silver-Derived Antimicrobial Coatings for the Prevention of Microbial Biofilms in Metal Pipes. *Water Air Soil Pollut* **232**, 1–11 (2021).

46. Towler, G. *et al.* CHEMICAL ENGINEERING DESIGN Principles, Practice and Economics of Plant and Process Design. (2008).

47. Sper Scientific Instruments | Environmental Measurement Instruments – Sper Scientific Direct. https://sperdirect.com/.

48. AEMO | Australian Energy Market Operator. https://aemo.com.au/.

49. HDPE Pipe Prices & Sizes Made Amazingly Easy by Matrix Piping! https://www.matrixpiping.com.au/pages/poly-pipe-prices.

50. Anglo Coal Australia Pty Ltd. *Report for Dawson Valley Pipeline Cost Estimate*. https://www.aer.gov.au/system/files/GHD%20report%2C%205%20February%202005%20%28public%20copy%29.pdf (2006).

51. Case Study Oven Mountain Pump Hydro Project Australian Industry Plan — Hughes et al — Hughes et al. https://www.hughesetal.com.au/case-study-oven-mountain-pump-hydro-project-australian-industry-plan.

52. Lithium-ion battery pack prices fall 20% in 2024. https://www.energy-storage.news/lithium-ion-battery-pack-prices-fall-20-in-2024-amidst-fight-for-market-share/.

53. 中国长江三峡工程开发总公司. https://web.archive.org/web/20090210072449/http://www.ctgpc.com.cn/sx/news.php?mNewsId=29096.

54. IRENA. Renewable Power Generation Costs In 2022 - Executive Summary. *International Renewable Energy Agency* 69 (2023).

55. Cost of Corrosion - Gas & Liquid Transmission Pipelines - Rust Bullet, LLC. https://www.rustbullet.com/cost-of-corrosion/advantage-gas-and-liquid-transmission/.

56. Gladstone Area Water Board. (2024).

57. O'callaghan, F. W. PIPELINE PERFORMANCE EXPERIENCES DURING SEISMIC EVENTS IN NEW ZEALAND, 1987 TO 2015.

58. Mazumder, R. K., Fan, X., Salman, A. M., Li, Y. & Yu, X. Framework for Seismic Damage and Renewal Cost Analysis of Buried Water Pipelines. *J Pipeline Syst Eng Pract* **11**, 04020038 (2020).

59. Update on the 2019 Tunnel Collapse and Canal Washout – Tunnel Repair or Replacement Options | IANR News. https://ianrnews.unl.edu/update-2019-tunnel-collapse-and-canal-washout-tunnel-repair-or-replacement-options?utm_source=chatgpt.com.

60. Muhlbauer, W. K. Absolute Risk Estimates. *Pipeline Risk Management Manual* 293–329 (2004) doi:10.1016/B978-075067579-6/50017-0.

61. Ayadi, A., Ghorbel, O., BenSalah, M. S. & Abid, M. A framework of monitoring water pipeline techniques based on sensors technologies. *Journal of King Saud University - Computer and Information Sciences* **34**, 47–57 (2022).

62. Fan, H., Tariq, S. & Zayed, T. Acoustic leak detection approaches for water pipelines. *Autom Constr* **138**, 104226 (2022).

63. Abbasi, Z., Niazi, H., Abdolrazzaghi, M., Chen, W. & Daneshmand, M. Monitoring pH Level Using High-Resolution Microwave Sensor for Mitigation of Stress Corrosion Cracking in Steel Pipelines. *IEEE Sens J* **20**, 7033–7043 (2020).

64. Fonseca, C. A. A. SCADA System of Pipelines. *Handbook of Pipeline Engineering* 1–28 (2024) doi:10.1007/978-3-031-05735-9_18-1.

65. Green, D. W. & Perry, R. H. *Perry's Chemical Engineers' Handbook, Eighth Edition*. *Perry's Chemical Engineers' Handbook* (McGraw-Hill Education, 2008).

66. Temperature and precipitation gridded data for global and regional domains derived from in-situ and satellite observations. https://cds.climate.copernicus.eu/datasets/insitu-gridded-observations-global-and-regional?tab=overview.

Appendix

Appendix 1: Decision matrix on selection of route

Route		WEIGHTING		1 (direct with tunnel)		2 (direct, no tunnel)		3 (Indirect via Xi'An)	
				value	weighted	value	weighted	value	weighted
OPEX		10		3	30	2	20	1	10
CAPEX		8		1	8	3	24	2	16
RISKS									
climate		5		2	10	2	10	2	10
seismic		2		1	2	2	4	3	6
monetary		3		1	3	3	9	2	6
PPP									
People		5		1	5	1	5	2	10
Profits		2		1	2	1	2	2	4
Planet		5		2	10	3	15	1	5
total		40			1.75		2.225		1.675

Appendix 2: LLM Prompt Philosophy

A combination of ChatGPT (utilising the GPT-4o engine) and Microsoft CoPilot were utilised to generate R code. Prompting was performed by requesting the LLM to utilise specific known equations from reputable references (e.g. Darcy's Law from Perry's Handbook[65].

Code was generated in short sections, tested, and compiled. For example,

1. Generate code to import and process DEM data.
2. Generate code to perform pathfinding between two latitude and longitude co-ordinates – output results on a DEM plot.
3. Modify the previous code to have a cost function between elevation and distance (where elevation costs x times as much as distance).
4. Modify the code to output the route over satellite imagery utilising a known GEOTIFF (map.tiff).

Each iteration was tested and debugged.

Appendix 3: Climactic Modelling

R code and figure for Fig. S1.

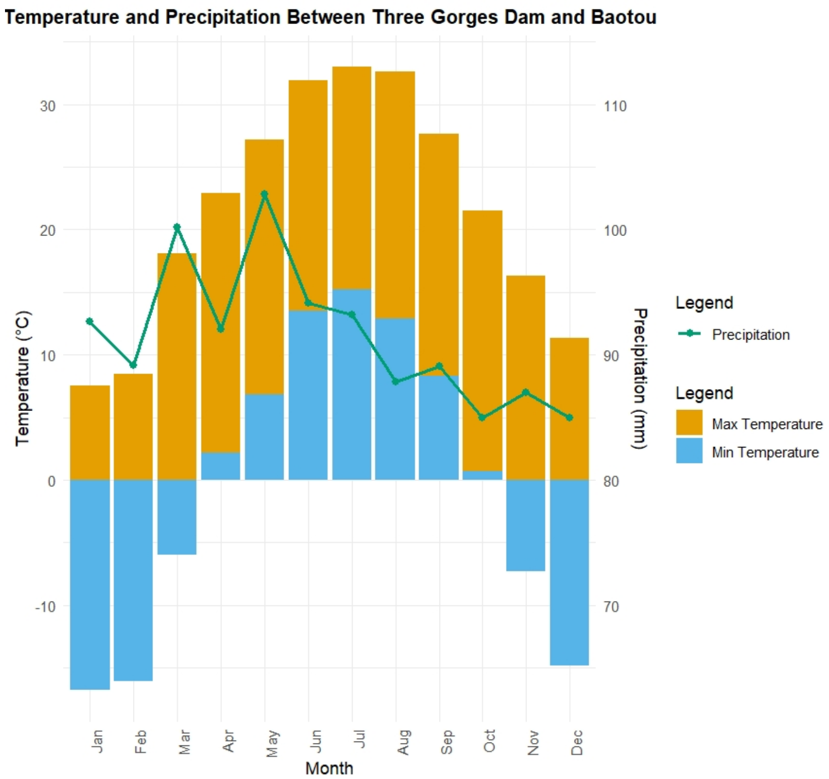


Fig. S1. The minimum and maximum temperature and precipitation for the general region between the TGD and Baotou. The data was derived from The Climate Data Store - "Temperature and precipitation data gridded data for global and regional domains derived from in-situ and satellite observations"[66].

```
library(ncdf4)

library(ggplot2)

library(dplyr)
```



```
max_temp_file_path <- "C:/Users/keith/Documents/max_temp.nc"

min_temp_file_path <- "C:/Users/keith/Documents/min_temp.nc"

nc_max_data <- nc_open(max_temp_file_path)

nc_min_data <- nc_open(min_temp_file_path)

lon <- ncvar_get(nc_max_data, "lon")

lat <- ncvar_get(nc_max_data, "lat")

time <- ncvar_get(nc_max_data, "time")

max_temperature <- ncvar_get(nc_max_data, "tasmax")

min_temperature <- ncvar_get(nc_min_data, "tasmin")

time <- as.Date(time, origin = "1970-01-01")
three_gorges_coords <- c(30.8231, 111.0031)

baotou_coords <- c(40.6562, 109.8345)

find_nearest_index <- function(array, value) {

  which.min(abs(array - value)) }

three_gorges_lat_idx <- find_nearest_index(lat, three_gorges_coords[1])

three_gorges_lon_idx <- find_nearest_index(lon, three_gorges_coords[2])

baotou_lat_idx <- find_nearest_index(lat, baotou_coords[1])

baotou_lon_idx <- find_nearest_index(lon, baotou_coords[2])

area_max_temp_data <- max_temperature[three_gorges_lon_idx:baotou_lon_idx, three_gorges_lat_idx:baotou_lat_idx, ]

area_min_temp_data <- min_temperature[three_gorges_lon_idx:baotou_lon_idx, three_gorges_lat_idx:baotou_lat_idx, ]

max_temp_per_time <- apply(area_max_temp_data, 3, max, na.rm = TRUE)

min_temp_per_time <- apply(area_min_temp_data, 3, min, na.rm = TRUE)

max_temp_df <- data.frame(

  time = time,

  temperature = max_temp_per_time,

  legend = "Max"

)

min_temp_df <- data.frame(

  time = time,
```



```
    temperature = min_temp_per_time,

    legend = "Min"

)

temp_df <- bind_rows(max_temp_df, min_temp_df)

temp_df <- temp_df %>%

    mutate(month = format(time, "%Y-%m")) %>%

    group_by(month, legend) %>%

    summarize(temperature = if_else(legend == "Max", max(temperature, na.rm = TRUE), min(temperature, na.rm = TRUE)))

precipitation_data <- data.frame(

    month = c("Jan", "Feb", "Mar", "Apr", "May", "Jun", "Jul", "Aug", "Sep", "Oct", "Nov", "Dec"),

    precipitation = c(92.69148, 89.14843, 100.20638, 92.00117, 102.80787, 94.14516, 93.18654, 87.84467, 89.05898,
84.96056, 87, 85)

)

temp_df <- temp_df %>%

    mutate(month_name = format(as.Date(paste0(month, "-01")), "%b"))

precipitation_data <- precipitation_data %>%

    mutate(month_name = factor(month, levels = month.abb))

temp_df$month_name <- factor(temp_df$month_name, levels = month.abb)

ggplot() +

    geom_bar(data = temp_df %>% filter(legend == "Max"), aes(x = month_name, y = temperature), stat = "identity", fill =
"#E69F00", position = "dodge") +

    geom_bar(data = temp_df %>% filter(legend == "Min"), aes(x = month_name, y = temperature), stat = "identity", fill =
"#56B4E9", position = position_dodge(width=0.9)) +

    geom_line(data = precipitation_data, aes(x = month_name, y = precipitation - 80, group = 1), color = "#009E73", size = 1)
+

    geom_point(data = precipitation_data, aes(x = month_name, y = precipitation - 80), color = "#009E73", size = 2) +

    scale_y_continuous(

        name = "Temperature (°C)",

        sec.axis = sec_axis(~ . + 80, name = "Precipitation (mm)")

    ) +

    labs(title = "Temperature and Precipitation Between Three Gorges Dam and Baotou",
```



```
        x = "Month",
        fill = "Legend",
        color = "Legend") +
    theme_minimal() +
    theme(axis.text.x = element_text(angle = 90, hjust = 1),
          plot.title = element_text(size = 12, hjust = 0.5, face = "bold"))
nc_close(nc_max_data)
nc_close(nc_min_data)
```


R code and figure for Fig. S2.

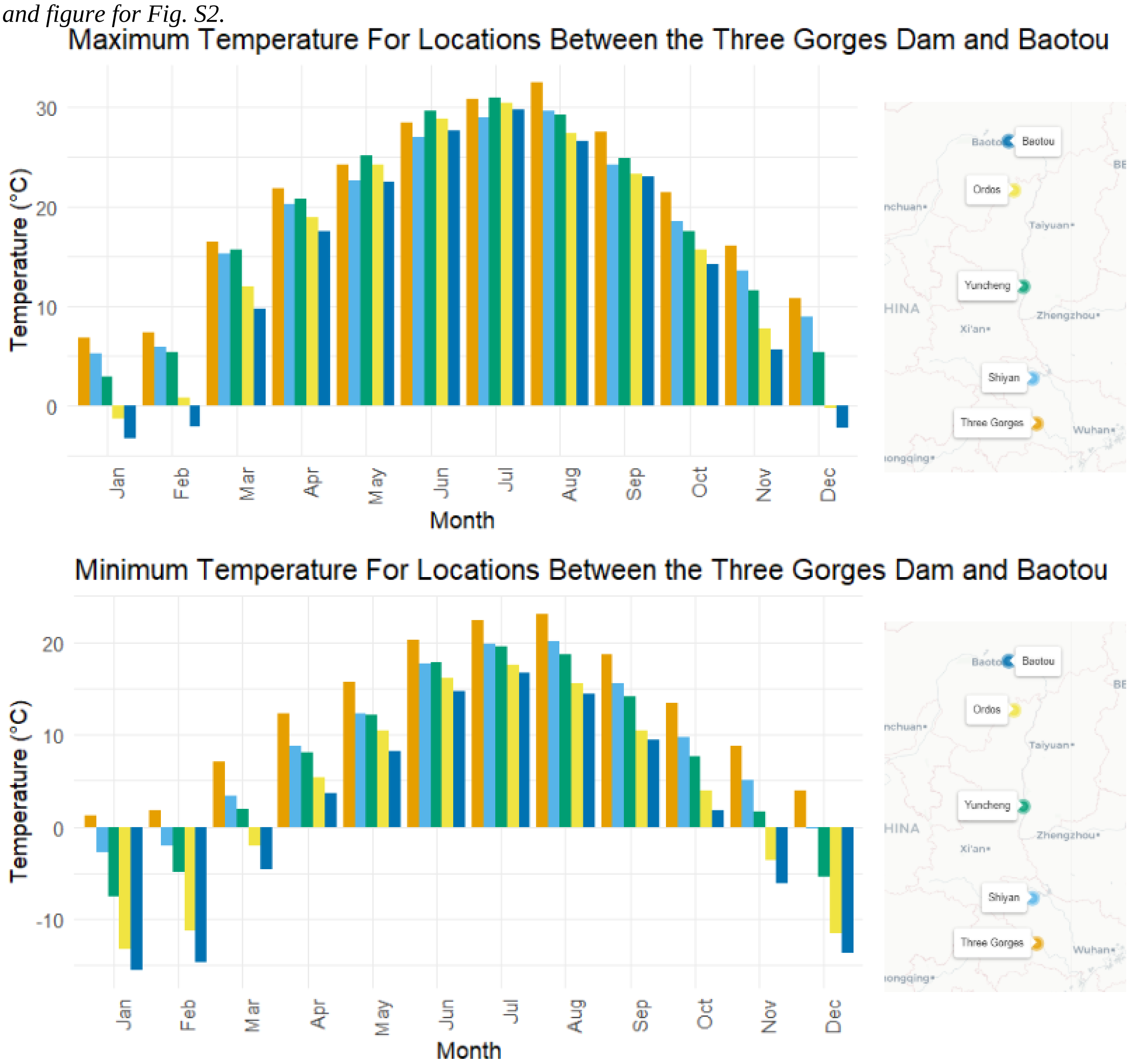


Fig. S2. Minimum and maximum temperatures for disparate nodes between the TGD and Baotou. The data was derived from The Climate Data Store - "Temperature and precipitation data gridded data for global and regional domains derived from in-situ and satellite observations"[66].

```
library(ncdf4)

library(ggplot2)

library(dplyr)

library(gridExtra)

library(ggthemes)
```



```
max_temp_file_path <- "C:/Users/keith/Documents/max_temp.nc"

min_temp_file_path <- "C:/Users/keith/Documents/min_temp.nc"

nc_max_data <- nc_open(max_temp_file_path)

nc_min_data <- nc_open(min_temp_file_path)

lon <- ncvar_get(nc_max_data, "lon")

lat <- ncvar_get(nc_max_data, "lat")

time <- ncvar_get(nc_max_data, "time")

max_temperature <- ncvar_get(nc_max_data, "tasmax")

min_temperature <- ncvar_get(nc_min_data, "tasmin")

time <- as.Date(time, origin = "1970-01-01")

coordinates <- list( c(30.8231, 111.0031), # Three Gorges c(32.46195, 110.8083), # Shiyan c(35.73965, 110.4188), # Yuncheng c(39.01735, 110.0293), # Ordos c(40.6562, 109.8345) # Baotou ) city_names <- c("Three Gorges", "Shiyan", "Yuncheng", "Ordos", "Baotou")

find_nearest_index <- function(array, value) { which.min(abs(array - value)) }

extract_temp_data <- function(coords, temperature) { temp_data <- list() for (coord in coords) { lat_idx <- find_nearest_index(lat, coord[1]) lon_idx <- find_nearest_index(lon, coord[2]) temp_data[[paste(coord[1], coord[2], sep = ", ")]] <- temperature[lon_idx, lat_idx, ] } return(temp_data) }

max_temp_data <- extract_temp_data(coordinates, max_temperature)

min_temp_data <- extract_temp_data(coordinates, min_temperature)

calculate_monthly_temp <- function(temp_data, time, type, city_names) { temp_df_list <- list() for (i in seq_along(temp_data)) { name <- names(temp_data)[i] city <- city_names[i] temp_df <- data.frame( time = time, temperature = temp_data[[name]], legend = paste(type, city) ) temp_df <- temp_df %>% mutate(month = format(time, "%Y-%m")) %>% group_by(month, legend) %>% summarize(temperature = if (type == "Max") max(temperature, na.rm = TRUE) else min(temperature, na.rm = TRUE)) temp_df_list[[name]] <- temp_df } return(do.call(rbind, temp_df_list)) }

max_temp_df <- calculate_monthly_temp(max_temp_data, time, "Max", city_names)

min_temp_df <- calculate_monthly_temp(min_temp_data, time, "Min", city_names)

temp_df_max <- max_temp_df

temp_df_min <- min_temp_df

temp_df_max <- temp_df_max %>% mutate(month_name = format(as.Date(paste0(month, "-01")), "%b")) temp_df_min <- temp_df_min %>% mutate(month_name = format(as.Date(paste0(month, "-01")), "%b"))

temp_df_max$month_name <- factor(temp_df_max$month_name, levels = month.abb) temp_df_min$month_name <- factor(temp_df_min$month_name, levels = month.abb)
```



```
city_order <- c("Three Gorges", "Shiyan", "Yuncheng", "Ordos", "Baotou")

temp_df_max$legend <- factor(temp_df_max$legend, levels = paste("Max", city_order))

temp_df_min$legend <- factor(temp_df_min$legend, levels = paste("Min", city_order))

colorblind_palette <- c( "#E69F00", # Orange "#56B4E9", # Sky Blue "#009E73", # Bluish Green "#F0E442", # Yellow
"#D55E00" # Vermillion )

p1 <- ggplot(temp_df_max, aes(x = month_name, y = temperature, fill = legend)) + geom_bar(stat = "identity", position =
"dodge") + labs(title = "Maximum Temperature For Locations Between the Three Gorges Dam and Baotou", x = "Month", y
= "Temperature (°C)", fill = "Legend") + scale_fill_manual(values = colorblind_palette) + # Use colorblind-friendly colors
theme_minimal() + theme(axis.text.x = element_text(angle = 90, hjust = 1))

p2 <- ggplot(temp_df_min, aes(x = month_name, y = temperature, fill = legend)) + geom_bar(stat = "identity", position =
"dodge") + labs(title = "Minimum Temperature For Locations Between the Three Gorges Dam and Baotou", x = "Month", y
= "Temperature (°C)", fill = "Legend") + scale_fill_manual(values = colorblind_palette) + # Use colorblind-friendly colors
theme_minimal() + theme(axis.text.x = element_text(angle = 90, hjust = 1))

grid.arrange(p1, p2, ncol = 1)

library(leaflet)

locations <- data.frame(
  Name = c("Three Gorges", "Shiyan", "Yuncheng", "Ordos", "Baotou"),
  Latitude = c(30.8231, 32.46195, 35.73965, 39.01735, 40.6562),
  Longitude = c(111.0031, 110.8083, 110.4188, 110.0293, 109.8345),
  Color = c("#FF0000", "#808000", "#008080", "#0000FF", "#800080")
)
map <- leaflet(data = locations) %>%
  addProviderTiles(providers$CartoDB.Positron) %>%
  setView(lng = 110, lat = 35, zoom = 5)
map <- map %>%
  addCircleMarkers(
    lng = ~Longitude,
    lat = ~Latitude,
    color = ~Color,
    label = ~Name,
    labelOptions = labelOptions(noHide = TRUE, direction = 'auto'),
    radius = 5,
    fillOpacity = 0.8
  )
Map
```


Appendix 4: Pathfinding Code

The following code utilises NASA DEM data[21] and computes the optimal path between two lat / long co-ordinates. Output is a .GPX route file (to be processed in a different R script).

```
gc()

# Load required libraries
library(terra)
library(gdistance)
library(sf)
library(pbapply)
library(raster)  # Added raster package for conversion
library(ggplot2)
library(viridis)

# Define node coordinates
nodes <- data.frame(
  name = c("Three Gorges Dam", "Baotou"),
  lon = c(111.0037, 109.8402),
  lat = c(30.8233, 40.6578)
)

# Load or generate the reduced DEM file
# dem_path <- "Reduced_DEM.tif"
dem_path <- "Reduced_DEM.tif"
start_time_total <- Sys.time()  # Start total time tracking

start_time_dem_generation <- Sys.time()  # Start time for reduced DEM generation
if (!file.exists(dem_path)) {
  cat("Reduced DEM not found. Generating it from original DEM...\n")
  original_path <- "Merged_China_DEM.tif"
  if (!file.exists(original_path)) {
    stop("Error: Original DEM file not found at", original_path)
  }
  original_dem <- rast(original_path)
  reduced_dem <- aggregate(original_dem, fact = 4, fun = mean, na.rm = TRUE)  # Reduce
resolution
  writeRaster(reduced_dem, dem_path, overwrite = TRUE)
  cat("Reduced DEM saved as", dem_path, "\n")
}
end_time_dem_generation <- Sys.time()
cat("Time taken for reduced DEM generation: ", difftime(end_time_dem_generation,
start_time_dem_generation, units = "mins"), "\n")

# Load the reduced DEM
cat("Loading DEM data...\n")
dem_raster <- rast(dem_path)

# Define bounding box coordinates for the new region
min_lon <- 106  # Minimum longitude (105°E)
max_lon <- 116  # Maximum longitude (120°E)
min_lat <- 30   # Minimum latitude (25°N)
max_lat <- 42   # Maximum latitude (45°N)

# Set bounding box for elevation data
```



```
cat("Setting bounding box from 105°E to 120°E and 25°N to 45°N...\n")
dem_bbox <- c(xmin = min_lon, xmax = max_lon, ymin = min_lat, ymax = max_lat)

# Crop the DEM to the bounding box region
cat("Cropping DEM to the new bounding box...\n")
dem_raster <- crop(dem_raster, dem_bbox)

# Check for NA values
cat("Checking for NA values in DEM...\n")
dem_raster[is.na(dem_raster)] <- max(values(dem_raster), na.rm = TRUE)  # Assign high
cost to NA

# Set cache directory for performance improvement
cache_dir <- "F:/DEMs/cache"
if (!dir.exists(cache_dir)) dir.create(cache_dir, recursive = TRUE)
terraOptions(tempdir = cache_dir)

# Convert DEM to RasterLayer for compatibility with gdistance
cat("Converting SpatRaster to RasterLayer for transition matrix computation...\n")
dem_raster_layer <- raster(dem_raster)

# Convert DEM to transition matrix with adjusted cost for elevation
cat("Computing transition matrix with adjusted cost for elevation...\n")
start_time_transition <- Sys.time()  # Start time for transition matrix computation
progress_bar <- txtProgressBar(min = 0, max = 1, style = 3)

tryCatch({
  cost_surface <- transition(dem_raster_layer, transitionFunction = function(x) {
    # Calculate the average elevation value
    val <- mean(x, na.rm = TRUE)

    # Calculate the elevation change (difference) and distance
    elevation_change <- max(x, na.rm = TRUE) - min(x, na.rm = TRUE)
    distance <- sqrt(sum(diff(c(x[1], x[2]))^2))  # Euclidean distance between two points

    # Apply the weight factor for elevation change
    elevation_cost <- 0.00015 * elevation_change  # Elevation cost is 10 times the distance

    # Combine the distance cost and elevation cost
    total_cost <- distance + elevation_cost

    # Avoid negative or zero values
    if (total_cost > 0) {
      return(1 / total_cost)  # Inverse of total cost for transition matrix
    } else {
      return(Inf)  # Prevent negative or zero values
    }
  }, directions = 8, symm = FALSE)
  cost_surface <- geoCorrection(cost_surface, type = "c", multpl = FALSE)
  setTxtProgressBar(progress_bar, 1)
}, error = function(e) {
  stop("Memory error during transition matrix computation: ", e$message)
})

close(progress_bar)
end_time_transition <- Sys.time()
cat("Time taken for transition matrix computation: ", difftime(end_time_transition,
start_time_transition, units = "mins"), "\n")
```



```
# Convert nodes to spatial points
cat("Processing nodes...\n")
node_points <- st_as_sf(nodes, coords = c("lon", "lat"), crs = 4326)
node_points <- st_transform(node_points, crs = st_crs(dem_raster))
node_points <- st_geometry(node_points)  # Ensure geometry consistency

# Function to smooth path coordinates using smooth.spline
smooth_path <- function(path_sf) {
  coords <- st_coordinates(path_sf)
  smoothed_coords <- data.frame(
    lon = smooth.spline(coords[, 1])$y,  # Smooth the longitude
    lat = smooth.spline(coords[, 2])$y   # Smooth the latitude
  )

  # Create a new Simple Feature object with smoothed coordinates
  smoothed_path <- st_as_sf(st_sfc(st_linestring(as.matrix(smoothed_coords)), crs =
st_crs(path_sf)))
  return(smoothed_path)
}

# Initialize variable to accumulate total distance
total_distance <- 0

# Function to compute path between two nodes sequentially and print path distance
compute_path <- function(i) {
  cat("Computing path for", nodes$name[i], "to", nodes$name[i+1], "...\n")
  start_time_path <- Sys.time()  # Start time for path computation
  tryCatch({
    path <- shortestPath(cost_surface, as.numeric(st_coordinates(node_points[i])),
                         as.numeric(st_coordinates(node_points[i+1])), output = "SpatialLines")

    # Convert path to sf object
    path_sf <- st_as_sf(st_sfc(st_as_sfc(path), crs = st_crs(dem_raster)))

    # Smooth the path
    smoothed_path_sf <- smooth_path(path_sf)

    # Calculate total path length
    path_length <- st_length(smoothed_path_sf)  # Length of the path (in meters, depending on
CRS)
    cat("Total path length from", nodes$name[i], "to", nodes$name[i+1], ":",
round(path_length, 2), "meters\n")

    # Accumulate the path length in total_distance
    total_distance <<- total_distance + as.numeric(path_length)  # Add the path length to the
total distance

    return(smoothed_path_sf)  # Return the smoothed path
  }, error = function(e) {
    cat("Error computing path:", e$message, "\n")
    return(NULL)
  })
  end_time_path <- Sys.time()
  cat("Time taken for path from", nodes$name[i], "to", nodes$name[i+1], ":",
difftime(end_time_path, start_time_path, units = "secs"), "\n")
}
```



```
# Compute paths sequentially with progress bar
cat("Computing paths sequentially to reduce RAM usage...\n")
progress_bar <- txtProgressBar(min = 0, max = nrow(nodes) - 1, style = 3)
paths <- vector("list", length = nrow(nodes) - 1)
for (i in 1:(nrow(nodes) - 1)) {
  paths[[i]] <- compute_path(i)
  setTxtProgressBar(progress_bar, i)
}
close(progress_bar)


# Save paths
cat("Saving computed paths...\n")
valid_paths <- paths[!sapply(paths, is.null)]

if (length(valid_paths) > 0) {
  geometries <- do.call(c, lapply(valid_paths, st_geometry))
  combined_path <- st_union(st_sfc(geometries, crs = st_crs(dem_raster)))
  if (st_geometry_type(combined_path) == "MULTILINESTRING") {
    combined_path <- st_line_merge(combined_path)
  }
  combined_sf <- st_sf(geometry = combined_path, crs = st_crs(dem_raster))

  # Write to GPX
  st_write(combined_sf, "computed_paths_smoothed.gpx", driver = "GPX", delete_layer =
TRUE)

  cat("Pathfinding complete! Saved as GPX.\n")
} else {
  cat("No valid paths computed.\n")
}

# Print total distance
cat("Total distance of all computed paths:", round(total_distance, 2), "meters\n")

# Convert the DEM raster to a data frame for plotting
cat("Converting DEM to data frame...\n")
start_time_plotting <- Sys.time()  # Start time for plotting
dem_raster_df <- as.data.frame(dem_raster, xy = TRUE)  # Convert to data frame with x, y
coordinates
colnames(dem_raster_df)[3] <- "elevation"  # Rename the third column to 'elevation'

paths_sf <- do.call(st_sfc, lapply(valid_paths, st_geometry))

# Plot the DEM with the computed paths
cat("Plotting smoothed paths over DEM...\n")
plot <- ggplot() +
  geom_tile(data = dem_raster_df, aes(x = x, y = y, fill = elevation)) +  # Correct column
reference
  scale_fill_viridis_c() +
  geom_sf(data = paths_sf, color = "red", size = 1) +
  geom_sf(data = node_points, color = "blue", size = 2) +
  labs(title = "Smoothed Pathfinding over DEM", x = "Longitude", y = "Latitude") +
  theme_minimal()

# Print the plot to the screen
print(plot)
```



```
# Save the plot to a file (e.g., as PNG or PDF)
ggsave("smoothed_pathfinding_plot.png", plot = plot, width = 10, height = 8, dpi = 300)  #
Adjust file format and resolution

end_time_plotting <- Sys.time()
cat("Time taken for plotting the DEM with smoothed paths: ", difftime(end_time_plotting,
start_time_plotting, units = "secs"), "\n")

end_time_total <- Sys.time()
cat("Total time taken for all computations: ", difftime(end_time_total, start_time_total, units
= "mins"), "\n")

### END ###
```


Appendix 5: Pressure Drop, Pumping Station Placement Code

The following code takes input from the previously generated path files (in .GPX form) and performs the following functions:

1. Places tunnel between two defined points in one path (in this case, path_1.gpx which is the direct / optimal route between TGD and Baotou).
2. Performs pressure drop calculations to determine static head and frictional losses across each path.
3. Plots the elevation profile of each path indicating position of pumping stations.

```
gc()

# Load necessary libraries
library(sf)
library(ggplot2)
library(dplyr)
library(units)
library(xml2)
library(ggspatial)
library(elevatr)

# User-defined variables
flow_rate <- 2  # m^3/s
pipe_diameter <- 2 # meters
fluid_density <- 1000
fluid_viscosity <- 0.001
epsilon <- 0.00001 # meters (typical for GFRP pipe)
max_pump_head <- 160  # m

# Define tunnel ranges by route
# Route 1: Direct TGD to Baotou
tunnel_ranges <- list(
  list(start_km = 1417, end_km = 1446.6)  # for Route 1
)

calculate_friction_factor <- function(RE, epsilon, pipe_diameter) {
  if (RE < 2000) {
    return(64 / RE)
  } else {
    colebrook <- function(f) {
      return(1 / sqrt(f) + 2 * log10(epsilon / (3.7 * pipe_diameter) + 2.51 / (RE * sqrt(f))))
    }
    solution <- uniroot(colebrook, c(0.0001, 1))
    return(solution$root)
  }
}

estimate_pump_stations <- function(path_data, max_pump_head) {
  head_loss <- 0
  station_locations <- c()
  for (i in 2:nrow(path_data)) {
    if (!is.na(path_data$pressure_loss_friction[i]) &&
!is.na(path_data$pressure_loss_elevation[i])) {
      head_loss <- head_loss + (path_data$pressure_loss_friction[i] +
path_data$pressure_loss_elevation[i]) / (fluid_density * 9.81)
    }
    if (head_loss >= max_pump_head) {
      station_locations <- c(station_locations, path_data$cumulative_distance[i])
```



```
      head_loss <- 0
    }
  }
  return(station_locations)
}

compute_station_pressures <- function(path_data) {
  pressure_table <- data.frame()
  segment_loss <- 0
  for (i in 2:nrow(path_data)) {
    segment_loss <- segment_loss + path_data$pressure_loss_friction[i] +
path_data$pressure_loss_elevation[i]
    if (path_data$pump_stations[i] == 1) {
      upstream <- segment_loss
      downstream <- upstream + (fluid_density * 9.81 * max_pump_head)
      pressure_table <- rbind(pressure_table, data.frame(
        path = path_data$path[i],
        station_index = i,
        distance_km = path_data$cumulative_distance[i],
        upstream_pressure_MPa = upstream / 1e6,
        downstream_pressure_MPa = downstream / 1e6
      ))
      segment_loss <- 0
    }
  }
  return(pressure_table)
}

insert_tunnel <- function(df, start_km, end_km) {
  i1 <- which.min(abs(df$cumulative_distance - start_km))
  i2 <- which.min(abs(df$cumulative_distance - end_km))
  if (i2 > i1 + 1) {
    n_interp <- i2 - i1 - 1
    lon_seq <- seq(df$lon[i1], df$lon[i2], length.out = n_interp + 2)[-c(1, n_interp + 2)]
    lat_seq <- seq(df$lat[i1], df$lat[i2], length.out = n_interp + 2)[-c(1, n_interp + 2)]
    elev <- rep(min(df$elevation[i1], df$elevation[i2]), n_interp)  # flat tunnel
    tunnel_df <- data.frame(lon = lon_seq, lat = lat_seq, elevation = elev)
    df <- bind_rows(df[1:i1, ], tunnel_df, df[i2:nrow(df), ])
  }
  return(df)
}

process_gpx <- function(file_path, path_id, layer_name, apply_tunnel = FALSE,
tunnel_range = NULL) {
  gpx_data <- st_read(file_path, layer = layer_name, quiet = TRUE)
  if (nrow(gpx_data) == 0) stop(paste("No data in", file_path))

  gpx_points <- gpx_data %>%
    mutate(lon = st_coordinates(.)[,1], lat = st_coordinates(.)[,2]) %>%
    select(lon, lat)

  gpx_points <- gpx_points %>%
    mutate(prev_lon = lag(lon), prev_lat = lag(lat)) %>%
    rowwise() %>%
    mutate(distance = ifelse(is.na(prev_lon), 0,
                             geosphere::distHaversine(c(prev_lon, prev_lat), c(lon, lat)))) %>%
    ungroup() %>%
    mutate(cumulative_distance = cumsum(distance) / 1000)  # km
```

```
  elevations <- get_elev_point(st_as_sf(gpx_points, coords = c("lon", "lat"), crs = 4326),
                               prj = st_crs(4326)$proj4string, src = "aws")
  gpx_points$elevation <- elevations$elevation

  if (apply_tunnel && !is.null(tunnel_range)) {
    gpx_points <- insert_tunnel(gpx_points, tunnel_range$start_km, tunnel_range$end_km)
  }

  RE <- (4 * fluid_density * flow_rate) / (pi * fluid_viscosity * pipe_diameter)
  friction_factor <- calculate_friction_factor(RE, epsilon, pipe_diameter)

  gpx_points <- gpx_points %>%
    mutate(prev_elevation = lag(elevation, default = first(elevation)),
           elevation_change = elevation - prev_elevation,
           elevation_gain = ifelse(elevation_change > 0, elevation_change, 0),
           pipe_distance = sqrt(distance^2 + elevation_change^2),
           pressure_loss_friction = friction_factor * (pipe_distance / pipe_diameter) *
             (flow_rate^2 / (2 * 9.81 * (pipe_diameter / 2)^2)),
           pressure_loss_elevation = ifelse(elevation_change > 0, 9.81 * elevation_change *
fluid_density, 0),
           path = path_id)

  gpx_points$pump_stations <- 0
  pump_locations <- estimate_pump_stations(gpx_points, max_pump_head)
  gpx_points$pump_stations[gpx_points$cumulative_distance %in% pump_locations] <- 1

  return(gpx_points)
}

# Original
path1 <- process_gpx("path_1.gpx", "Direct TGD to Baotou", "route_points")
path2 <- process_gpx("path_2.gpx", "TGD to Baotou Via Xi'An", "track_points")

# With tunnels
path1_tunnel <- process_gpx("path_1.gpx", "TGD to Baotou (Tunneled)", "route_points",
TRUE, tunnel_ranges[[1]])

all_paths <- bind_rows(path1, path2, path1_tunnel)

# Compute pressure upstream/downstream of each pump station
pressure_table <- bind_rows(
  compute_station_pressures(path1),
  compute_station_pressures(path2),
  compute_station_pressures(path1_tunnel)
)

print(pressure_table)

# Plot elevation with overlaid paths and pumping stations
all_paths$path <- factor(all_paths$path, levels = c(
  "TGD to Baotou (Tunneled)",
  "Direct TGD to Baotou",
  "TGD to Baotou Via Xi'An"
))

plot <- ggplot(all_paths, aes(x = cumulative_distance, y = elevation, color = path, linetype =
path)) +
```



```
  geom_line(size = 0.5) +
  scale_linetype_manual(name = "Route", values = c(
    "TGD to Baotou (Tunneled)" = "dotted",
    "Direct TGD to Baotou" = "solid",
    "TGD to Baotou Via Xi'An" = "solid"
  )) +
  geom_point(data = all_paths %>% filter(pump_stations == 1 & !grepl("Tunneled", path)),
             aes(x = cumulative_distance, y = elevation, shape = "Booster Pumping Station"),
             color = "black", fill = "white", size = 2, stroke = 0.5) +
  scale_color_manual(values = c(
    "Direct TGD to Baotou" = "seagreen",
    "TGD to Baotou Via Xi'An" = "coral",
    "TGD to Baotou (Tunneled)" = "red"
  )) +
  scale_shape_manual(name = "", values = c("Booster Pumping Station" = 21)) +
  labs(title = "Elevation Profile with Booster Pumping Stations",
       x = "Distance Along Route (km)",
       y = "Elevation (m)",
       color = "Route") +
  theme_minimal() +
  theme(legend.position = c(0.05, 0.95),
        legend.justification = c("left", "top"),
        legend.box = "vertical",
        text = element_text(size = 14))

plot <- plot +
  geom_vline(data = tibble(
    km = c(tunnel_ranges[[1]]$start_km, tunnel_ranges[[1]]$end_km),
    label = rep("Tunnel Entry/Exit", 2)
  ),
  aes(xintercept = km), linetype = "dashed", color = "gray40", linewidth = 0.3) +
  geom_text(data = tibble(
    km = c(tunnel_ranges[[1]]$start_km, tunnel_ranges[[1]]$end_km),
    elevation = rep(Inf, 2),
    label = c("Tunnel In", "Tunnel Out")
  ),
  aes(x = km, y = elevation, label = label),
  inherit.aes = FALSE,
  vjust = -0.2, size = 2.5, color = "gray30")

print(plot)

# Compute required totals per route with units
total_summary <- all_paths %>%
  group_by(path) %>%
  summarise(
    total_distance_km = set_units(sum(distance, na.rm = TRUE) / 1000, "km"),
    total_elevation_gain = set_units(max(elevation, na.rm = TRUE) - min(elevation, na.rm =
TRUE), "m"),
    cumulative_elevation_gain = set_units(sum(ifelse(elevation_change > 0, elevation_change,
0), na.rm = TRUE), "m"),
    total_static_pressure_drop = set_units(9.81 * (max(elevation, na.rm = TRUE) -
min(elevation, na.rm = TRUE)) * fluid_density, "Pa"),
    total_frictional_pressure_drop = set_units(sum(pressure_loss_friction, na.rm = TRUE),
"Pa"),
    number_of_pump_stations = sum(pump_stations, na.rm = TRUE),
    .groups = "drop"
  )
```



```
total_summary <- total_summary %>%
  mutate(
    total_head_m = (total_static_pressure_drop + total_frictional_pressure_drop) /
(fluid_density * 9.81),
    total_hydraulic_power_W = fluid_density * 9.81 * flow_rate * set_units(total_head_m,
NULL),
    total_pump_power_W = total_hydraulic_power_W / 0.828,
    total_pump_power_MW = set_units(total_pump_power_W, "MW")
  )

print(total_summary)

### END ###
```

Appendix 6: Matthew Code (rename)

Earthquake frequency code

```
    # gc()
    #
    #
    # # Load necessary libraries
    # library(tidyverse)
    # library(rpart)
    # library(geosphere)
    # library(elevatr)
    # library(sf)
    # library(ggmap)
    # library(ggplot2)
    # library(ggspatial)
    # library(dplyr)
    # library(units)
    # library(lpSolve)
    # library(caret)
    #
    #
    # # Load your TSV file (earthquake history data)
    # earthquake_data <- read.delim("seismic_data.tsv", sep = "\t", header = TRUE)
    # earthquake_data <- earthquake_data %>%
    #   rename(lat = Latitude, lon = Longitude, magnitude = Mag)
    #
    #
    # # Remove rows with NA values in magnitude and depth
    # earthquake_data_filter <- earthquake_data %>%
    #   filter(((lat > 39) & (lat < 41)) & ((lon > 112) & (lon < 115)))

    gc()

    # Load necessary libraries
    library(dplyr)
    library(ggplot2)

    # Function to read and filter earthquake data
    filter_earthquake_data <- function(file_path, min_lat, max_lat, min_long, max_long) {
      # Read the TSV file
      earthquake_data <- read.delim(file_path, header = TRUE, sep = "\t")
```



```
  # Filter data based on latitude and longitude range
  filtered_data <- earthquake_data %>%
    filter(Latitude >= min_lat & Latitude <= max_lat & Longitude >= min_long & Longitude <= max_long)

  return(filtered_data)
}

# Function to perform Gutenberg-Richter analysis
gutenberg_richter_analysis <- function(filtered_data) {
  # Calculate the cumulative number of earthquakes for each magnitude
  magnitude_counts <- filtered_data %>%
    group_by(Mag) %>%
    summarise(count = n()) %>%
    arrange(desc(Mag)) %>%
    mutate(cumulative_count = cumsum(count))

  # Perform linear regression on log10(cumulative_count) vs. Mag
  magnitude_counts <- magnitude_counts %>%
    mutate(log_cumulative_count = log10(cumulative_count))

  # Filter out non-finite values
  magnitude_counts <- magnitude_counts %>%
    filter(is.finite(log_cumulative_count))

  regression_model <- lm(log_cumulative_count ~ Mag, data = magnitude_counts)

  # Extract coefficients
  a <- coef(regression_model)[1]
  b <- -coef(regression_model)[2]

  return(list(a = a, b = b, model = regression_model, data = magnitude_counts))
}

# Function to calculate the probability of an earthquake of magnitude >= M
calculate_probability <- function(a, b, M) {
  # Calculate the number of earthquakes of magnitude M or greater
  log_N = a - b * M
  N = 10^log_N

  # Calculate the total number of earthquakes
  total_earthquakes = 10^a

  # Calculate the probability
  probability = N / total_earthquakes

  return(probability)
}

# Function to calculate the average number of years before an earthquake of magnitude >= M
calculate_average_years <- function(a, b, M) {
  # Calculate the number of earthquakes of magnitude M or greater
  log_N = a - b * M
  N = 10^log_N

  # Calculate the total number of earthquakes per year
  total_earthquakes_per_year = 10^a
```



```
  # Calculate the probability
  probability = N / total_earthquakes_per_year

  # Calculate the average number of years before an earthquake of magnitude M or greater
  average_years = 1 / probability

  return(average_years)
}

# Main function
main <- function() {
  # Define file path and latitude/longitude range
  file_path <- "seismic_data.tsv"
  min_lat <- 38
  max_lat <- 40
  min_long <- 110
  max_long <- 115

  # Filter earthquake data
  filtered_data <- filter_earthquake_data(file_path, min_lat, max_lat, min_long, max_long)
  print(filtered_data)
  # Perform Gutenberg-Richter analysis
  analysis_results <- gutenberg_richter_analysis(filtered_data)

  # Print results
  cat("Gutenberg-Richter coefficients:\n")
  cat("a =", analysis_results$a, "\n")
  cat("b =", analysis_results$b, "\n")

  # Calculate and print the probability of an earthquake of magnitude 4 or higher
  probability <- calculate_probability(analysis_results$a, analysis_results$b, 4)
  cat("Probability of an earthquake of magnitude 4 or higher:", probability, "\n")

  # Calculate and print the average number of years before an earthquake of magnitude 4 or higher
  average_years <- calculate_average_years(analysis_results$a, analysis_results$b, 5)
  cat("Average number of years before an earthquake of magnitude 4 or higher:", average_years, "\n")

  # Plot the results
  ggplot(analysis_results$data, aes(x = Mag, y = log_cumulative_count)) +
    geom_point() +
    geom_smooth(method = "lm", se = FALSE, color = "blue") +
    labs(title = "Gutenberg-Richter Relationship",
         x = "Magnitude",
         y = "Log10(Cumulative Count)") +
    theme_minimal()
}

# Run the main function
main()
```

Pipe failure code

```
# Load necessary library
library(dplyr)

# Define a function to calculate the reliability function
reliability_function <- function(lambda, t) {
  exp(-lambda * t)
```



```
}

# Define a function to calculate the cumulative distribution function (CDF)
cdf_function <- function(lambda, t) {
  1 - exp(-lambda * t)
}

# Define a function to calculate the maintenance schedule
maintenance_schedule <- function(pipeline_sections, time_period) {
  pipeline_sections %>%
    rowwise() %>%
    mutate(
      AdjustedFailureRate = FailureRate * Length,  # Adjust failure rate by length
      Reliability = reliability_function(AdjustedFailureRate, time_period),
      CDF = cdf_function(AdjustedFailureRate, time_period),
      MaintenanceNeeded = ifelse(CDF > 0.5, "Yes", "No")
    )
}

# Define a function to calculate the optimal maintenance interval
optimal_maintenance_interval <- function(pipeline_sections, target_reliability) {
  cumulative_failure_rate <- sum(pipeline_sections$FailureRate * pipeline_sections$Length)
  interval <- -log(target_reliability) / cumulative_failure_rate
  return(interval)
}

# Example pipeline sections with different materials, failure rates, and lengths
pipeline_sections <- data.frame(
  Section = c("Stainless Steel", "Polyethylene", "GFRP"),
  FailureRate = c(0.01, 0.02, 00.00029),  # Failure rates per year per unit length
  Length = c(0, 0, 1926)  # Lengths of each section in kilometers
)

# Define the target reliability (e.g., 0.95 for 95% reliability)
target_reliability <- 0.95

# Calculate the optimal maintenance interval
maintenance_interval <- optimal_maintenance_interval(pipeline_sections, target_reliability)

# Print the maintenance interval
cat("Optimal Maintenance Interval (years):", maintenance_interval, "\n")
cat("Optimal Maintenance Interval (months):", maintenance_interval*12, "\n")

# Calculate the maintenance schedule for the given time period
time_period <- maintenance_interval
maintenance_schedule(pipeline_sections, time_period)
```

Appendix 7: Costing/Energy

Costing was calculated in excel using various assumptions/calculations

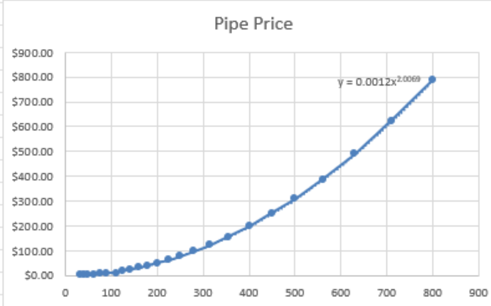
Pipeline Material Cost:

*All costs are per meter

Size (mm)	PE100 PN4 SDR41	PE100 PN6.3 SDR26	PE100 PN8 SDR21	PE100 PN10 SDR17	PE100 PN12.5 SDR13.6	PE100 PN16 SDR11
32	-	-	$1.11	$1.30	$1.65	$1.89
40	-	-	$1.66	$2.05	$2.49	$3.01
50	-	-	$2.63	$3.16	$3.84	$4.67
63	-	$3.32	$4.02	$5.04	$6.12	$7.38
75	-	$4.70	$5.75	$7.11	$8.54	$10.31
90	-	$6.83	$8.32	$8.56	$12.27	$14.94
110	$6.55	$10.23	$12.47	$10.23	$18.41	$22.15
125	$8.60	$12.91	$15.94	$19.42	$23.73	$28.74
140	$10.78	$16.29	$19.89	$24.37	$29.71	$35.82
160	$13.97	$21.37	$26.13	$31.67	$38.78	$47.02
180	$17.39	$26.61	$32.85	$40.25	$49.23	$59.43
200	$21.38	$33.00	$40.68	$49.65	$60.36	$73.28
225	$27.06	$41.47	$51.42	$62.98	$76.66	$92.76
250	$33.90	$51.38	$62.92	$77.19	$94.44	$114.09
280	$42.02	$64.09	$79.42	$96.97	$118.33	$143.03
315	$52.78	$81.64	$99.79	$122.80	$149.97	$181.05
355	$67.14	$103.16	$126.68	$156.27	$190.11	$229.79
400	$85.10	$130.83	$161.54	$197.50	$241.10	$291.76
450	$107.32	$165.43	$204.30	$250.24	$305.41	$369.47
500	$133.60	$204.06	$252.04	$308.25	$376.83	$455.87
560	$166.35	$255.76	$315.45	$387.30	$472.73	$571.06
630	$210.47	$324.10	$398.48	$489.41	$597.57	$723.60
710	$267.83	$411.97	$507.41	$622.44	$759.16	-
800	$339.62	$521.76	$643.10	$789.27	$962.97	-

https://www.matrixpiping.com.au/pages/poly-pipe-prices

Size	Price
32	$1.30
40	$2.05
50	$3.16
63	$5.04
75	$7.11
90	$8.56
110	$10.23
125	$19.42
140	$24.37
160	$31.67
180	$40.25
200	$49.65
225	$62.98
250	$77.19
280	$96.97
315	$122.80
355	$156.27
400	$197.50
450	$250.24
500	$308.25
560	$387.30
630	$489.41
710	$622.44
800	$789.27



Extrapolated pipe	755	* In Australia
	529	*In China
$/km/1m dia	528,604	China Adjusted
$/km/1m dia	755,149	Unadjusted

3. **Plastics & Composites**
   - China produces a large volume of polymers and composite materials.
   - Australia imports many plastic raw materials, making costs **20-40% higher.**

Battery costs

	Option A	Option B	Option C		Notes
Number of stations	22	23	34		
Total energy req (MWh p.a)	289080	359160	420480		*MWh/year * annual energy requirement
Load per station (MW)	1.50	1.78	1.41		* With annual load of xMW, finding amount per station by dividing by number of stations and assuming equal load across all stations for calculation purposes
Backup supply (MWh)	12	14.26	11.29		*8-hour backup supply
Total Battery Capacity (MWh)	264	328	384		*backup supply * # of stations
Cost	23,232,000	28,864,000	33,792,000		* cost of battery $88 USD/kWh

CAPEX

Category	Option A: Tunneling (USD)	Option B: Pumping (USD)	Option C: Indirect (USD)	Justification
Land Acquisition	142,349,288	144,449,278	193,724,031	USD $2,500/mu (mu=666.67 m2), 20m width
Pipeline Materials	2,163,720,000	2,195,640,000	2,944,620,000	Pipeline cost @ USD $760k/km, based on total route distance, scaling factor of 1.5 to account for monitoring systems, fittings etc
Pumping Infrastructure	506,000,000	552,000,000	1,207,000,000	Based on word table in section 3
Water Intake System	1,000,000,000	1,000,000,000	1,000,000,000	
Construction Costs	2,442,726,000	2,478,762,000	3,324,321,000	$33,000/in/km (cpi adjusted from 1996)
Tunneling Costs (Option A)	6,000,000,000	-	-	Tunnelling cost estimate by matt
Pumping Over Mountain Costs (Option B)	-	1,000,000,000	1,500,000,000	Additional construction for elevation and terrain access
Battery Cost	23,232,000	28,864,000	33,792,000	Calculated on Battery Reqs sheet
Contingency (10%)	1,225,479,529	737,085,128	1,016,966,503	10% contingency for unforeseen CAPEX elements
Total	13,518,506,817	8,151,800,406	11,235,423,535	added 15mil from Treatment cost

Tunnel Option OPEX

Year	Energy Cost (USD)	Maintenance (USD)	Labor (USD)	Admin & Insurance (USD)	Environmental Monitoring (USD)	Total OPEX (USD)	Assumptions
2025	13,490,400	11,190,000	43,274,400	13,518,507	4,476,000	85,949,307	* assuming operation all year round, 8760MWh annually
2026	13,895,112	11,525,700	44,572,632	13,924,062	4,610,280	88,527,786	*Hydro = 42 USD /MWh
2027	14,311,965	11,871,471	45,909,811	14,341,784	4,748,588	91,183,620	*assuming 1/3rd hydro 2/3 solar
2028	14,741,324	12,227,615	47,287,105	14,772,037	4,891,046	93,919,128	*Solar = 49 USD/MWh
2029	15,183,564	12,594,444	48,705,718	15,215,199	5,037,777	96,736,702	* energy cost = (((1/3)*42*8760*PUMP REQ)+((2/3)*49*8760*PUMP REQ))
2030	15,639,071	12,972,277	50,166,890	15,671,654	5,188,910	99,638,803	* Assuming 3% cost increases per year
2031	16,108,243	13,361,445	51,671,897	16,141,804	5,344,578	102,627,967	*Assuming pump efficiency 0.75
2032	16,591,490	13,762,289	53,222,054	16,626,058	5,504,915	105,706,806	*assume $5000/km maintenance annually
2033	17,089,235	14,175,157	54,818,715	17,124,840	5,670,062	108,878,010	*Assume labour costs = 2% pipeline capex + altitude construction
2034	17,601,912	14,600,412	56,463,277	17,638,585	5,840,164	112,144,351	*Assume environmental monitoring = 40% maintenance
2035	18,129,970	15,038,424	58,157,175	18,167,743	6,015,369	115,508,681	*assume insurance rate of 5% capex split over 50 years with 3% interest p.a
2036	18,673,869	15,489,577	59,901,890	18,712,775	6,195,830	118,973,942	*added 1.7mil to maintenance from karinnas opex
….	….	….	….	….	….	….	….

Direct Mountain Option OPEX

Year	Energy Cost (USD)	Maintenance (USD)	Labor (USD)	Admin & Insurance (USD)	Environmental Monitoring (USD)	Total OPEX (USD)	Assumptions
2025	16,760,800	11,330,000	63,912,800	8,151,800	4,532,000	104,687,400	* assuming operation all year round, 8760MWh annually
2026	17,263,624	11,669,900	65,830,184	8,396,354	4,667,960	107,828,022	*Hydro = 42 USD /MWh
2027	17,781,533	12,019,997	67,805,090	8,648,245	4,807,999	111,062,863	*assuming 1/3rd hydro 2/3 solar
2028	18,314,979	12,380,597	69,839,242	8,907,692	4,952,239	114,394,749	*Solar = 49 USD/MWh
2029	18,864,428	12,752,015	71,934,419	9,174,923	5,100,806	117,826,591	* energy cost = (((1/3)*42*8760*PUMP REQ)+((2/3)*49*8760*PUMP REQ))
2030	19,430,361	13,134,575	74,092,452	9,450,171	5,253,830	121,361,389	* Assuming 3% cost increases per year
2031	20,013,272	13,528,613	76,315,226	9,733,676	5,411,445	125,002,231	*Assuming pump efficiency 0.75
2032	20,613,670	13,934,471	78,604,682	10,025,686	5,573,788	128,752,298	*assume $5000/km maintenance annually
2033	21,232,080	14,352,505	80,962,823	10,326,457	5,741,002	132,614,867	*Assume labour costs = 2% pipeline capex + altitude construction
2034	21,869,042	14,783,080	83,391,708	10,636,251	5,913,232	136,593,313	*Assume environmental monitoring = 40% maintenance
2035	22,525,114	15,226,573	85,893,459	10,955,338	6,090,629	140,691,112	*assume insurance rate of 5% capex split over 50 years with 3% interest p.a
2036	23,200,867	15,683,370	88,470,263	11,283,998	6,273,348	144,911,845	*added 1.7mil to maintenance from karinnas opex
....	....	....	....	....	....	....	....

Indirect Route OPEX

Year	Energy Cost (USD)	Maintenance (USD)	Labor (USD)	Admin & Insurance (USD)	Environmental Monitoring (USD)	Total OPEX (USD)	Assumptions
2025	19,622,400	14,615,000	88,892,400	11,235,424	5,846,000.0	140,211,224	* assuming operation all year round, 8760MWh annually
2026	20,211,072	15,053,450	91,559,172	11,572,486	6,021,380.0	144,417,560	*Hydro = 42 USD /MWh
2027	20,817,404	15,505,054	94,305,947	11,919,661	6,202,021.4	148,750,087	*assuming 1/3rd hydro 2/3 solar
2028	21,441,926	15,970,205	97,135,126	12,277,251	6,388,082.0	153,212,590	*Solar = 49 USD/MWh
2029	22,085,184	16,449,311	100,049,179	12,645,568	6,579,724.5	157,808,967	* energy cost = (((1/3)*42*8760*PUMP REQ)+((2/3)*49*8760*PUMP REQ))
2030	22,747,740	16,942,791	103,050,655	13,024,935	6,777,116.2	162,543,236	* Assuming 3% cost increases per year
2031	23,430,172	17,451,074	106,142,174	13,415,683	6,980,429.7	167,419,533	*Assuming pump efficiency 0.75
2032	24,133,077	17,974,607	109,326,440	13,818,154	7,189,842.6	172,442,119	*assume $5000/km maintenance annually
2033	24,857,069	18,513,845	112,606,233	14,232,698	7,405,537.9	177,615,383	*Assume labour costs = 2% pipeline capex + altitude construction
2034	25,602,781	19,069,260	115,984,420	14,659,679	7,627,704.0	182,943,845	*Assume environmental monitoring = 40% maintenance
2035	26,370,865	19,641,338	119,463,952	15,099,470	7,856,535.2	188,432,160	*assume insurance rate of 5% capex split over 50 years with 3% interest p.a
2036	27,161,991	20,230,578	123,047,871	15,552,454	8,092,231.2	194,085,125	*added 1.7mil to maintenance from karinnas opex
....	....	....	....	....	....	....	....

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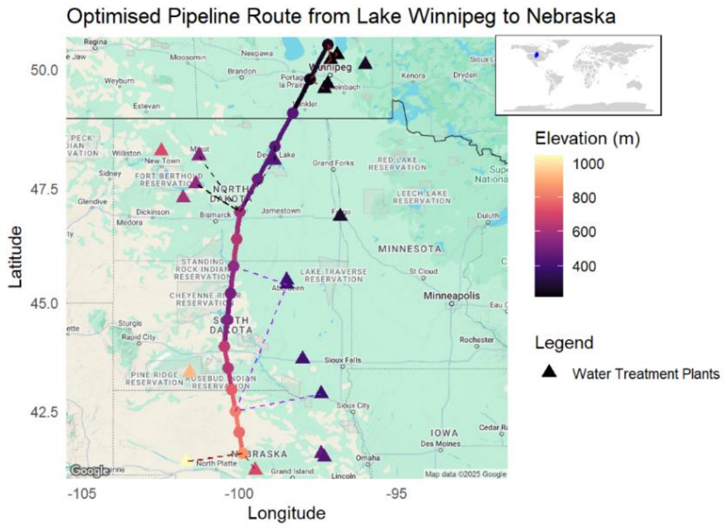
A Sustainable Solution to Water Scarcity: Modelling the feasibility of a Canada to Great Plains Water Pipeline

Nicholas Lawton-Wade, Tom Croxford, James Rene and Enoch Chelliah

E-mail: tcro6810@uni.sydney.edu.au

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*

SJIE 1(4) X-X (2025)

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).*

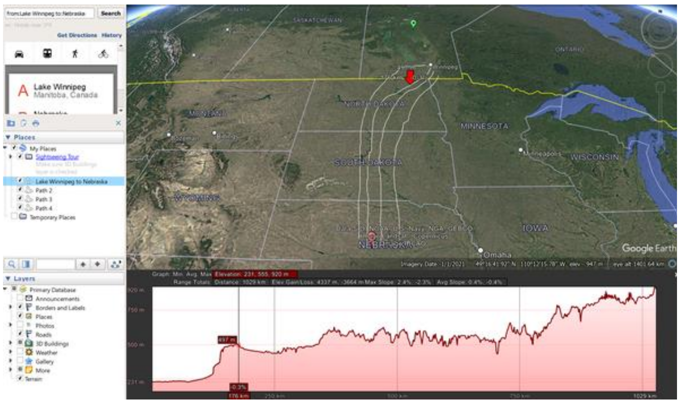


Figure 1: Google Earth Pro view of water pipeline

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.

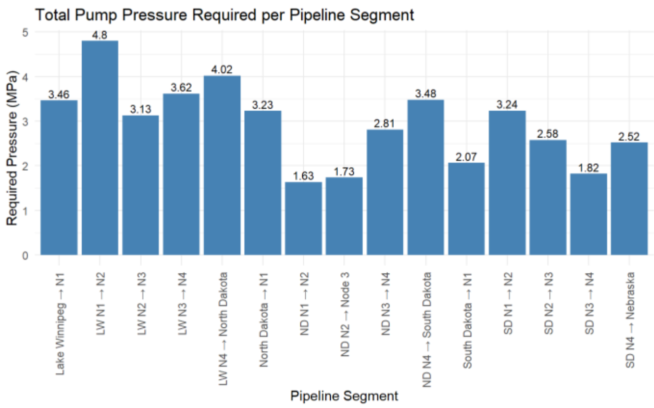


Figure 2: Total Operating Pressure Pipeline Segments (excluding pressure losses).

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.

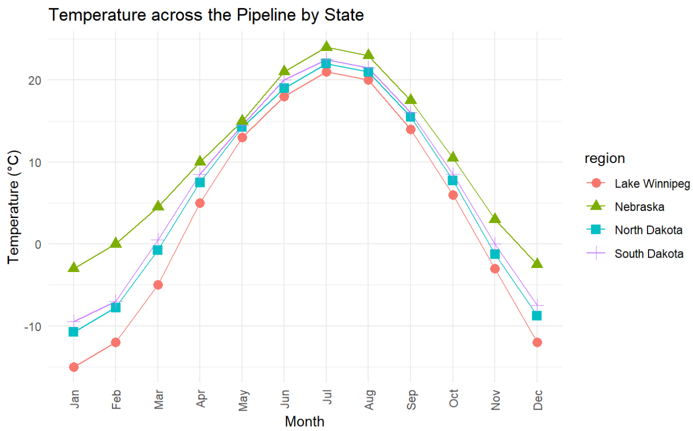


Figure 3: Temperature Profile of pipeline segments vs Month

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 $\times 10^{-6}$/°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.

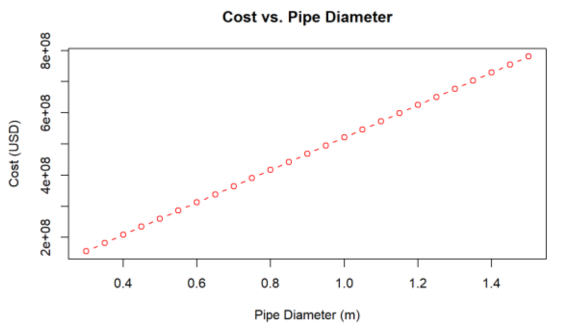

*Figure **Error! No text of specified style in document.** Costs vs Pipe Diameter*

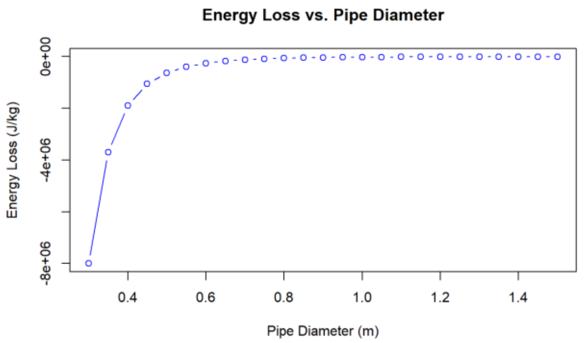

*Figure **Error! No text of specified style in document.** Energy Efficiency vs Pipe Diameter*

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

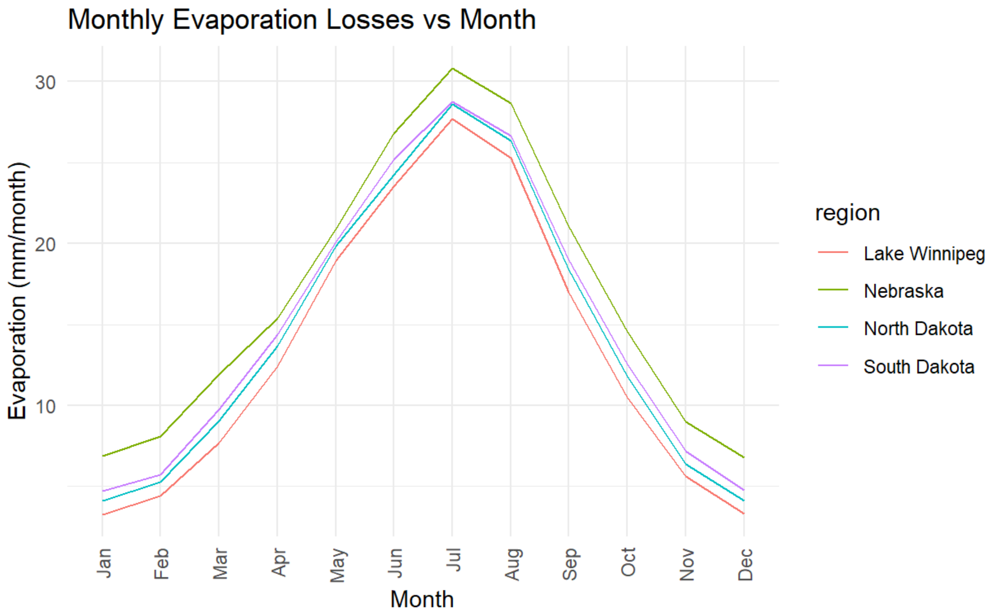

*Figure **Error! No text of specified style in document.**-1 Evaporation Losses Across the Pipeline are considered, especially if not buried below the Frost Line, in the event of project changes.*

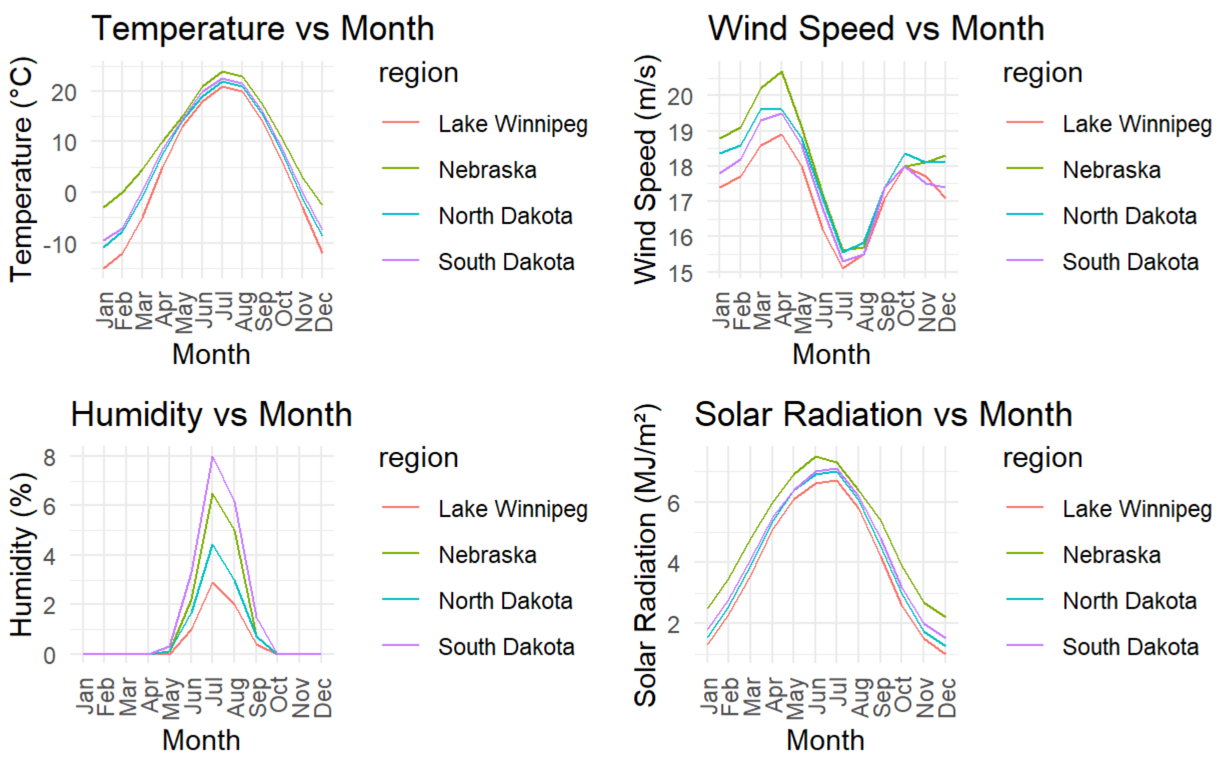

*Figure **Error! No text of specified style in document.**-27:**Error! No text of specified style in document.**-3 Temperature, Wind Speed, Humidity, and Solar Radiation data for areas of concern regarding pipeline construction.*

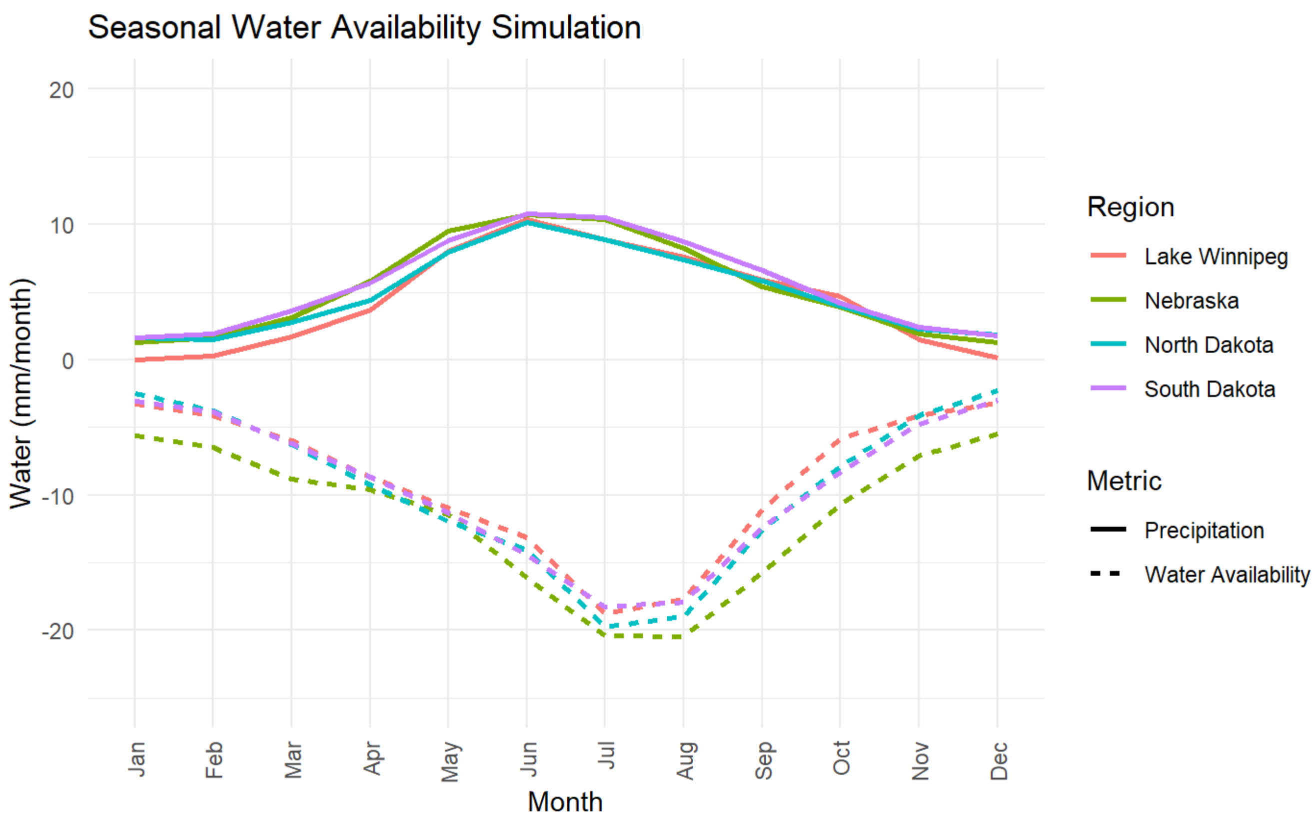

*Figure **Error! No text of specified style in document.**-48:**Error! No text of specified style in document.**-5 Seasonal Water Availability Simulation across the pipeline.*

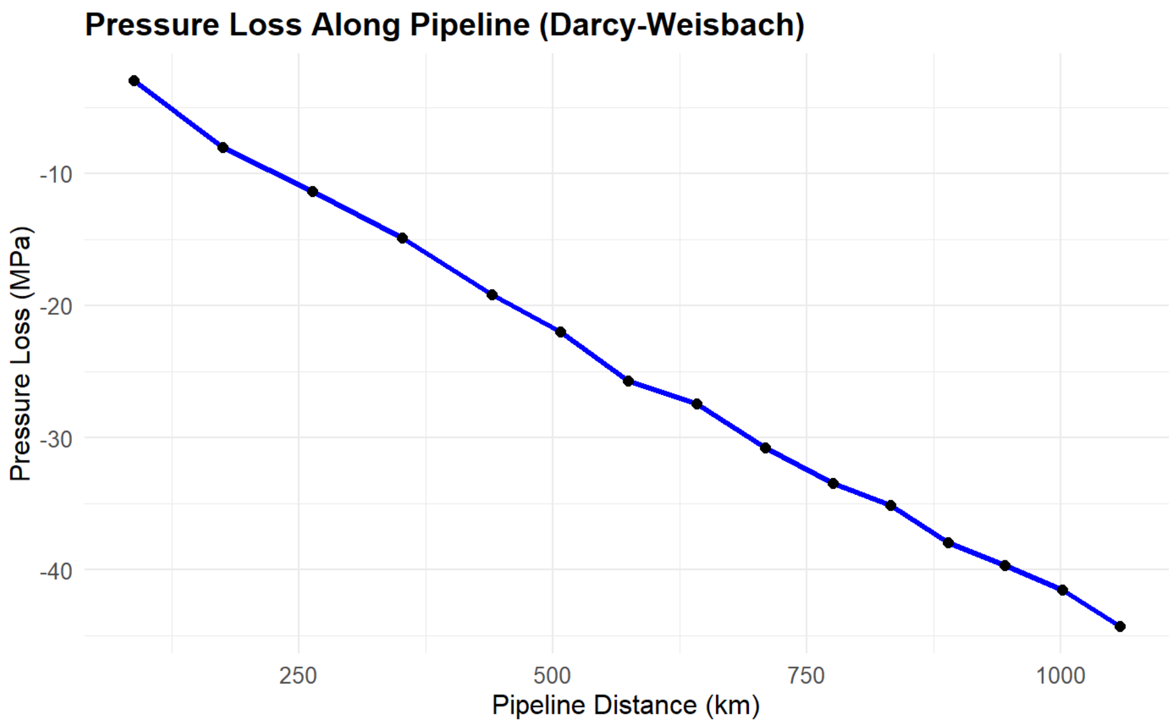

*Figure **Error! No text of specified style in document.**-6 Pressure Loss Along Pipeline.*

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 m³/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 m³ 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 m³/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/m³ (Chapter 4), for 547.5M m³/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		

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Addressing Climate-Induced Water Supply Imbalance Through Inter-Basin Water Transfer Modelling: A Philippine Case Study

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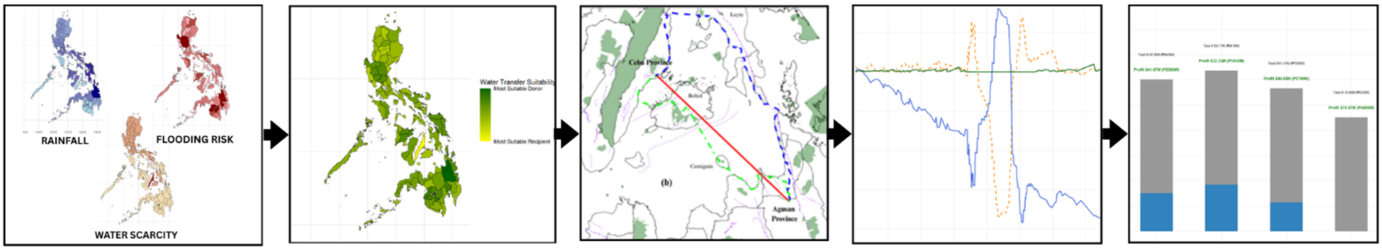
Graphical Abstract



Regional rainfall, flooding, and water scarcity assessment | Donor-recipient basin identification | Pipeline routing evaluation | Hydraulic modeling and pump head simulation | Project impact assessment

Abstract

This study assesses the feasibility of an inter-basin water transfer (IBWT) system in the Philippines, designed to alleviate water scarcity by connecting the flood-prone Agusan River Basin, with an annual surplus of 4,647.43 million cubic meters (MCM), to the water-scarce Mananga River Basin in Cebu, currently facing a significant deficit. The proposed pipeline, approximately 412 kilometers long, aims to supply up to 63.9 MCM/yr. Hydraulic modeling and detailed geospatial analyses support the optimization of the pipeline route, minimizing environmental impact and construction costs while promoting sustainable development. The project is anticipated to create around 639 construction jobs and 142 operational positions, fostering local employment and economic development. It is projected to increase water availability in Cebu by 58.26 liters per capita per day, addressing the acute water scarcity that affects the region. Economic projections estimate substantial profits, with the IBWT system expected to generate a net present value of USD 194.04 million, highlighting its potential as a profitable and sustainable infrastructure investment. Finally, while environmental concerns may persist, these can be mitigated through currently existing hydropower infrastructure instead of fossil fuel utilization for pumping, reducing CO_2 emissions from 14.85 tons to 0.51 tons of CO_2 annually. Overall, this outlines a critical step toward long-term water security and climate-resilient infrastructure development in the Philippines.

Keywords: interbasin water transfer, IBWT, water scarcity, pipeline, hydraulic modelling, geospatial analysis, sustainable infrastructure, climate resilience, water security, economic feasibility, regional development, Philippines, Agusan River Basin, Mananga River Basin

1. Introduction

Global water demand has been increasing by approximately 1% per year since the 1980s, driven by rapid population growth, urbanization, and economic development.[1] As a result, water distribution has become a critical aspect of infrastructure planning, particularly in countries where seasonal changes and distinct geographical features lead to significant variations in water availability. Large-scale inter-basin water transfer projects, such as China's South-to-North Water Diversion Project which is estimated to transfer over 44.8 billion cubic meters annually by 2050, demonstrate the necessity of engineered solutions to address regional water shortages.[2]

In the Philippines, an archipelagic nation with a complex hydrological landscape, water distribution remains a persistent challenge. Its National Economic and Development Authority (NEDA) has highlighted that rainfall variability between islands is a key driver of uneven water distribution across the archipelago.[3] The country experiences distinct wet and dry seasons, influenced by monsoons and an average of 20 tropical cyclones entering the Philippine Area of Responsibility (PAR) annually, leading to alternating periods of water abundance and scarcity. [4] This results in extreme hydrological conditions, with some regions receiving as little as 965 mm of rainfall per year, while others exceed 4,064 mm.[5]

Flooding is a major consequence of excessive rainfall, particularly in river basins and low-lying urban areas. Dam overflows and riverine flooding frequently displace communities, damage infrastructure, and disrupt economic activities. For instance, the 2020 Typhoon Ulysses (Vamco) led to catastrophic flooding in Luzon, submerging parts of Metro Manila and forcing the release of excess water from Magat Dam, which contributed to the inundation of downstream areas.[6] Meanwhile, prolonged dry periods contribute to drought conditions, reduced agricultural productivity, and water shortages, particularly in Metro Manila and Cebu, where high population densities strain existing water resources.[7] The El Niño phenomenon exacerbates these challenges, with the 2015–2016 El Niño event causing a significant decline in dam water levels, leading to rotational water interruptions and reduced irrigation supply.[8] Previous mitigation efforts, including rainwater harvesting, dam construction, and small-scale water redistribution systems, have provided partial relief but remain insufficient to address large-scale water imbalances. Future strategies aim to enhance water security through improved reservoir management, desalination, and expanded inter-basin water transfer projects.[9]

Given these challenges, there is an urgent need for sustainable and large-scale solutions. This study explores the feasibility of a basin-to-basin water transfer approach as a long-term strategy for addressing water distribution disparities in the Philippines. By facilitating the movement of excess water from surplus regions to deficit areas, this approach offers a balanced and adaptive solution to the country's hydrological extremes. Previous studies have demonstrated the effectiveness of inter-basin water transfer in managing water supply reliability in other countries, suggesting that this method could provide a viable solution for the Philippines as well[10]. The potential benefits, limitations, and implementation considerations of this strategy are discussed to contribute to the ongoing discourse on national water security and resilience.

In addition to identifying the basins in need of transferring and determining the optimal pipeline routing, key technical specifications, including pump hydraulic modelling, pumping selection and layout are analyzed. This also assesses the project's cost, energy consumption, environmental impact, and potential risks, ensuring a balance between efficiency and sustainability. To achieve this, the pipeline system are modeled in R, integrating data from various sources to analyze geographical and meteorological factors such as topography, rainfall, sea depth, and fault lines, as well as infrastructure constraints related to piping and pump performance. This comprehensive approach aims to optimize the pipeline's design, ensuring its technical and economic viability as a long-term water security solution for the region.

2. Methodology

2.1 Source and Recipient Basins Selection

The source and recipient basins were identified using hydrological, climatological, and water availability indicators commonly applied in prior water transfer studies [11] namely, annual precipitation, river flood risk, and water scarcity. Rainfall data (1991–2020) came from the World Bank Climate Knowledge Portal,[12] while flood and scarcity risks were obtained from the Global Facility for Disaster Reduction and Recovery (GFDRR's) ThinkHazard! Tool,[13] categorized from Very Low to High. Flood risk reflects river overflow potential based on rainfall, catchment, and drainage characteristics, while scarcity indicates the supply-demand balance, with "High" denoting critical shortages. To ensure data-driven comparisons and minimize bias, a normalized scoring system was used: rainfall and flood risk scored 1–4, and water scarcity was inverted to ensure higher values meant more availability. Provincial scores were averaged from all three indicators, and regional scores were based on provincial means. The region with the highest score became the source basin (water surplus), while the lowest-scoring region became the recipient basin. The largest river basin for each identified regions was designated as either the donor or recipient basin.

2.2 Pipeline Routing

Three distinct pathway scenarios to determine optimal inter-basin transfer route were considered: the first used straight line route to minimize pipe length, while the second and third used R's Open Source Routing Machine (OSRM) to follow existing infrastructure via predefined waypoints. Routing computations used the WGS84 (EPSG:4236) spatial reference system. Publicly available spatial datasets and shapefiles including provincial boundaries, active faultlines[15] and environmentally protected areas[16] were integrated. Routes were visaulized using R's ggplot2 and cowplot, with elevation profiles generated from AWS Terrain Tiles via elevator::get_elev_point(). Cumulative pipe lengths were calculated by combining geodesic distances (distGeo()) with elevation differentials. Each route was evealuated in terms of pipe length, elevation gain, and intersection with protected areas and fault lines.

2.3 Hydraulic Modelling

Water availability was assessed using current and projected hydrological data. The Agusan River Basin has an estimated surplus of 4,647.43 MCM/year (2020),[75] while the Mananga River Basin in Metro Cebu faces a growing deficit—from 25.0 MCM/year (2020) to up to 63.8 MCM/year by 2050 in a 1-in-10 dry year.[76] The system was modelled as a closed, pressurized HDPE pipeline (1.0 m diameter), chosen for its durability, flexibility, and resistance to corrosion, slow degradation and seismic activity.[17] Flow velocity was kept near 3.0 m/s to optimize energy use, limit head loss, and reduce water hammer risk[18,19] Scenario-specific discharge rates were converted to flow rates (m^3/s). Elevation profiles were derived from AWS Terrain Tiles, and frictional head loss was estimated using both the Darcy–Weisbach ($f = 0.015$) and Hazen–Williams ($C = 130$) equations, with coefficients appropriate for clean, large-diameter HDPE.[20] Minor losses were inferred using a Position_Y index. Total head loss included frictional, minor, and elevation losses. Pumping head requirements were calculated via Bernoulli's equation, assuming 75% pump efficiency, typical in preliminary large-scale water system design.

2.4 Pump Modelling

Three classes of centrifugal pumps from three different suppliers that are widely commercially available and are able to meet the head and flowrate requirements were considered through cross-checking with vendor data. The use of similar pumps is well-established in international water diversion projects, including China's South–North Water Transfer Project and Nepal's Melamchi Water Supply Project, which both employed centrifugal pumps to align system hydraulics with elevation gradients and pressure head requirements. The models were verified to be appropriate for inter-basin transfer infrastructure and are consistent with technical standards for long-distance, pressurized pipeline systems. For each flow scenario (Baseline, Moderate Dry Year, and Max Resilience), the number of pumps required in parallel (to meet volumetric flow) and in series (to overcome total dynamic head) was computed using standard hydraulic equations, including Bernoulli's equation and the Darcy-Weisbach method. Pump station placements were optimized by interpolating across the pressure head profile, ensuring evenly spaced locations above sea level to reduce the risk of cavitation and facilitate maintenance.

2.5 Project Costing

Water transfer configurations for different pump models were assessed using 20-year lifecycle (typical for pump lifespan), cost framework, incorporating captial expenditure (CAPEX), operational expenditure (OPEX), and projected revenue, with all cash flows discounted at an 8% rate. Pump capital costs were estimated using a parametric approach based on market pricing for commercially avaialble large-scale centrifugal pumps. The Grundfos CRN 185-6, a high-pressure vertical multistage pump, served as the baseline at USD 76,500 (₱4.28 million) based on average online prices. Lower-end systems, such as axial split pumps for high-flow, low-head scenarios, were priced at 0.5× the baseline while higher-end horizontal multistage pumps were set at 1.5× to account for differences in design complexity, materials, and auxiliary equipment needs as previously done in pump costing scaleup for similar projects[21]. To estimate total infrastructure CAPEX, percent-based multipliers were applied relative to the pump CAPEX based on guidance for standard practices for incorporating infrastructure components into overall project costs[67]: Pipeline at 1500%, Civil Works at 150%, Land at 50%, Electrical, SCADA, and smart automation systems at 50%, Environmental considerations at 12.5%, and Contingency at 200%. OPEX calculations were based on pump power demand using power calculations from pump head, with electricity priced at ₱9.00/kWh (USD 0.16/kWh), escalating by 4% annually and including a 10% O&M markup in line with local power company pricing.[22] Revenue projections assumed an initial tariff of ₱35/m^3 (USD 0.63), rising 3% annually, within typical local water pricing ranges.[24] Net present values (NPVs) were calculated for CAPEX, OPEX, and revenues, and used to evaluate each configuration through total lifecycle cost, NPV, and Benefit-Cost Ratio (BCR), consistent with global water infrastructure appraisal practices.[22]

2.6 Risk Mitigation and Water Transfer Optimization

A modified semi-quantitative risk assessment methodology[31] was used to identify, prioritize risks and optimise water transfer. A Risk Register was developed under the Triple

Bottom Line (TBL) framework, encompassing economic, environmental, and social dimensions. Risks were identified through a synthesis of academic literature, engineering guidelines, and infrastructure planning protocols relevant to long-distance water transfer. Each risk was assigned a likelihood (L) and impact (I) score on a five-point ordinal scale, ranging from 1 (rare/insignificant) to 5 (almost certain/catastrophic). The overall risk score was calculated using a multiplicative formula (Risk = L × I), which is widely adopted in infrastructure risk management due to its balance between rigor and usability.[68] Mitigation strategies were developed for each identified risk by analyzing typical failure modes, systemic vulnerabilities, and engineering control options. Cost estimates were incorporated as a percentage of the total project budget, referencing similar international water transfer initiatives. This method provides a structured basis for comparing and optimizing risk mitigation efforts, aligning with best practices recommended for water infrastructure under uncertainty.[69]

2.7 Project Impacts

The proposed water transfer project is expected to deliver substantial social, economic, and environmental benefits. Socially, the improvement in water supply was estimated by comparing Cebu's existing water deficit with the projected annual transfer volume, expressed in liters per capita per day (LPCD) using population and demand projections from the National Water Resources Board (NWRB). Job creation was to be 12.5 jobs per million USD CAPEX[70] and 8 jobs per million USD OPEX[71] linking employment generation to both capital and operational costs, based on previous water infrastructure projects.

Economic impact was assessed by incorporating risk mitigation costs into the lifecycle model using percentage estimates informed by global infrastructure guidelines. Seismic, typhoon, marine, and community-related measures were costed at 2–8% of total project cost, depending on severity and exposure. Scenario-based allowances were set at 28% (Base + Minimum) for total cost of risk mitigation strategies[32-56], 34% (Base + Average), and 40% (Base + Maximum), falling within the 10–40% range recommended by the World Bank and Asian Development Bank for complex, hazard-prone infrastructure projects.

Environmentally, carbon emissions from pumping were estimated using the formula CO_2 = Energy Use × Emission Factor, with emission factors of 0.7 kg CO_2/kWh for fossil-based electricity and 0.024 kg CO_2/kWh for hydropower, Philippine Department of Energy and International Hydropower Association estimates.[73,74] Marine pipeline impacts was assessed based on the estimated area of seabed disturbed, extracting the length of piping underneath the water. This is based on marine impact studies of offshore construction activities, which highlight the potential harm to benthic habitats.

3. Results and Discussions

3.1 Basin Selection

The provincial-level analysis of rainfall distribution, flooding risks, and water scarcity across the Philippines reveals significant geographic disparities in water availability and associated vulnerabilities as illustrated in Figure 1. Regional ratings are summarised in S.1. Provinces in Caraga such as Agusan del Norte and Agusan del Sur experience notably high annual rainfall and severe flood risks, indicating substantial water surplus coupled with frequent flooding threats. Climate projections indicate increasing precipitation intensity in this region, with severe 24-hour rainfall events expected to rise significantly by mid-century, further exacerbating existing flood vulnerabilities.[25] On the other hand, provinces in Central

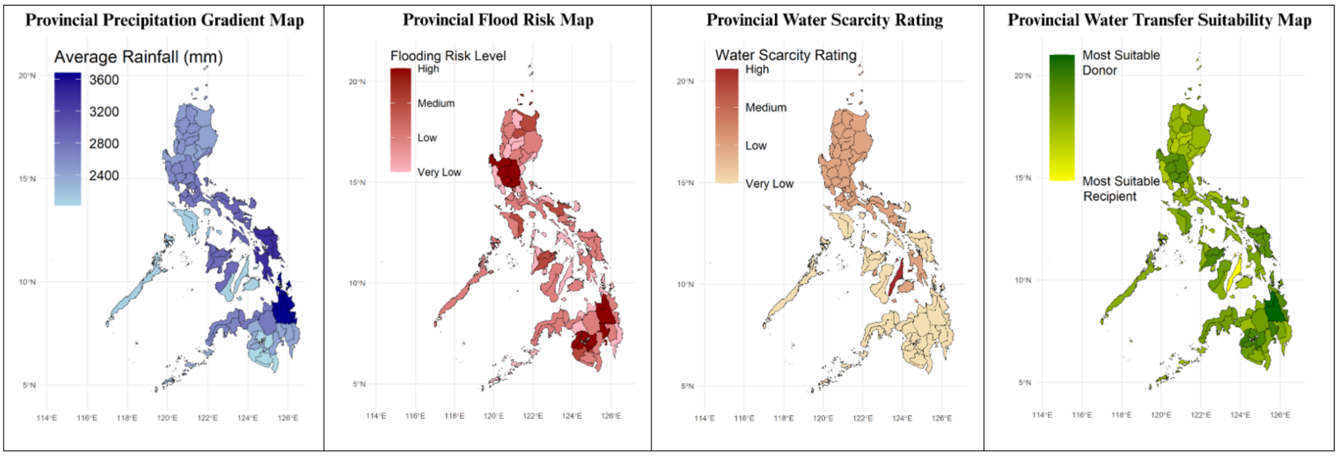


Figure 1. Heat maps for (from left to right): (a) annual precipitation, (b) flooding risk level, (c) water scarcity rating, and (d) overall water transfer suitability in the Philippines.

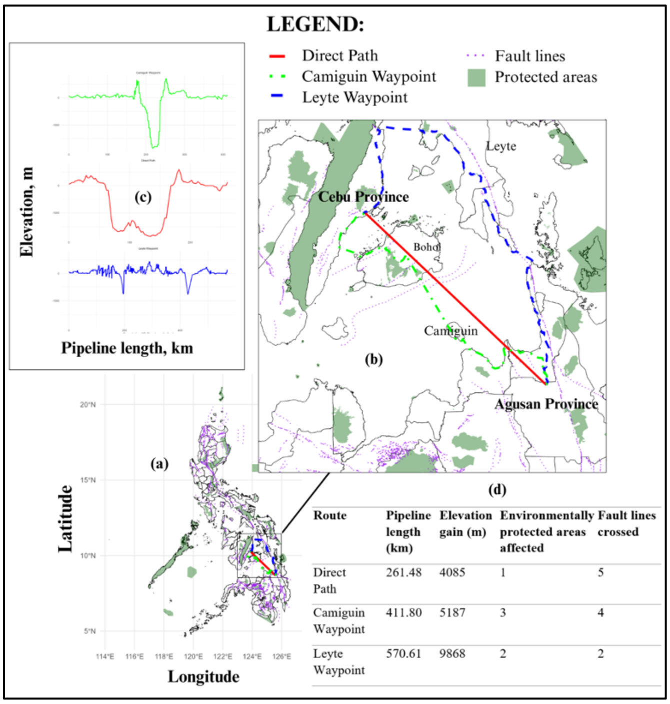
Visayas, particularly Cebu, experiences water scarcity, intensified by urbanization and high-water demand, with Metro Cebu classified as a water-critical area.[26]

These pronounced regional disparities underscore significant challenges in achieving equitable water distribution across the country and highlight an urgent need for integrated water management solutions. In Cebu, water scarcity is predominantly managed through intensive groundwater extraction and increasingly through desalination, which are practices that pose considerable sustainability concerns, including land subsidence from aquifer depletion and high operational energy costs.[27] Such localized measures, while providing short-term relief, often fail to address long-term sustainability and regional balance in water resource allocation.

Given these constraints, inter-basin water transfer (IBWT) emerges as a compelling alternative capable of sustainably reallocating water resources from surplus to deficit regions. Although large-scale IBWT implementations are currently limited in the Philippines, the approach aligns well with integrated water resources management (IWRM) principles promoting regional equity, efficient resource utilization, and resilience to climate variability.[29] Globally, IBWT projects such as China's South–North Water Transfer Project and India's Peninsular River Linking Project (Krishna–Pennar Link) have successfully demonstrated the ability of inter-basin schemes to mitigate flooding in donor basins and significantly alleviate water scarcity pressures in recipient regions.[30] Similarly, establishing an IBWT scheme from Agusan provinces to Cebu offers considerable potential to simultaneously address flooding risks in donor basins and alleviate persistent water shortages in recipient areas, thereby reducing dependency on unsustainable local water sources and promoting regional water security.

3.2. Pipeline Routing

Three water transfer pipeline routes were evaluated as shown in Figure 2. The Direct Path represented the shortest option (261 km) with minimal elevation gain (4,085 m). However, the viability of this path raises issues due to its intersection with multiple active fault lines and absence of support infrastructure, which substantially increases seismic risk, construction cost, and long-term maintenance difficulty.[32] Moreover, it is lacking existing road access which can complicate logistics for equipment delivery and emergency response.[28, 57]. In contrast, the Leyte Waypoint avoided sensitive geological and environmental features but has substantially increased pipeline length (571 km) and elevation gain (9,868 m), thereby more likely to increase infrastructure and energy costs due to higher pumping demands. The Camiguin Waypoint emerged as the optimal compromise. It balanced moderate increases in length (412 km) and elevation gain (5,187 m) with reduced seismic risks by intersecting fewer fault lines and minimizing environmental impacts on protected areas. Furthermore, using OSRM routing for existing road networks as guidance, this option provided practical construction advantages by leveraging developed road networks that reduces overall implementation risks and environmental disruption. A similar GIS-informed automatic pipeline routing project that avoids obstructions, irrigation areas, and restricted areas, was previously utilized in a piping project in Turkey[28] with estimated cost savings of 20%, highlighting the advantages of OSRM and similar routing approaches that integrate spatial analysis with practical infrastructure considerations which demonstrated effectiveness in optimizing pipeline projects by balancing environmental sensitivity, seismic resilience, and economic feasibility. Thus, the Camiguin Waypoint, satisfies the multi-criteria evaluation better and conseuquently provides a strong foundation for developing an effective and resilient inter-basin water transfer between Agusan and Cebu, potentially serving as a benchmark for future pipeline infrastructure planning within the Philippines and comparable global contexts.



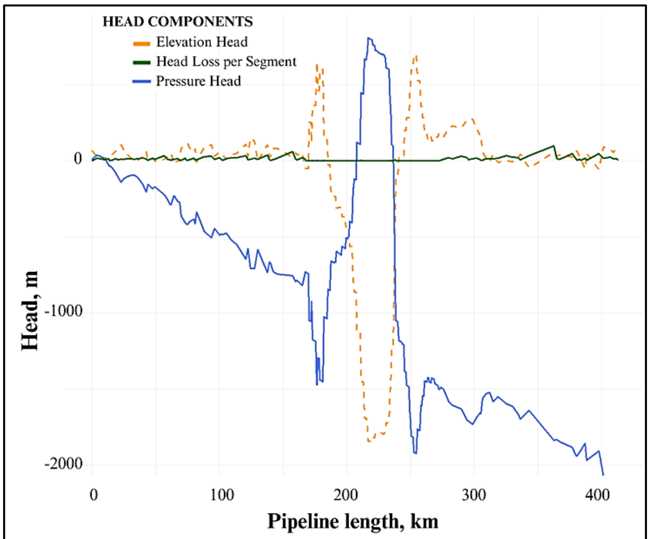
Route	Pipeline length (km)	Elevation gain (m)	Environmentally protected areas affected	Fault lines crossed
Direct Path	261.48	4085	1	5
Camiguin Waypoint	411.80	5187	3	4
Leyte Waypoint	570.61	9868	2	2

Figure 2. Pipeline routing showing (a) location of basins in the Philippines (b) three pipeline route options (c) elevation profile of the routes and (d) route features.

3.3. Hydraulic Modelling

Hydraulic modeling under the Baseline, Moderate Dry Year, and Maximum Resilience scenarios revealed significant differences in pumping head requirements shown in Figure 3. Under Baseline conditions, total head losses ranged from

195.4 m (Darcy–Weisbach) to 211.5 m (Hazen–Williams), indicating manageable pumping needs. In contrast, Moderate Dry Year and Maximum Resilience scenarios required significantly higher pumping heads, around 680–690 m and up to 1,220–1,294 m, respectively, due to increased frictional losses from higher flow rates. These results emphasize the need for optimized pipe sizing, routing, and pump station design to balance capital costs and long-term energy efficiency. While smaller diameters can reduce upfront costs, they increase flow velocity and friction losses, raising energy consumption and maintenance demands.[77] Thus, balancing the initial infrastructure investments against long-term energy efficiency becomes a critical consideration, particularly under scenarios designed to ensure maximum resilience and continuous water availability during extreme droughts or peak demand periods. Comparing friction loss models, Darcy–Weisbach produced slightly higher estimates than Hazen–Williams, particularly under high-flow conditions (e.g., Moderate Dry Year and Maximum Resilience).



Transfer Scenario	Minor Losses (m)	Major Losses (m)	Total Head Loss, Hf (m)	Elevation head, Δz (m)	Pressure head, ΔP (m)	Estimated Pumping head (m)
Baseline Scenario	3.15	DW: 192.24	DW+Minor: 195.39	22	0	217.39
		HW: 208.30	HW+Minor: 211.45	22	0	233.45
Moderate Dry Year	10.70	DW: 653.42	DW+Minor: 664.12	22	0	686.12
		HW:646.71	HW+Minor: 657.41	22	0	679.41
Maximum Resilience	20.5	DW: 1251.09	DW+Minor: 1271.58	22	0	1293.58
		HW:1180.13	HW+Minor: 1200.62	22	0	1222.62

Figure 3. Head profile and pumping requirements along the Camiguin pipeline for the different water transfer scenarios.

This observation aligns with the expectation that the Darcy-Weisbach method typically provides a more conservative estimate, especially beneficial when designing for extreme operational scenarios to ensure system reliability.[78] Such comparative analysis underscores the necessity of using multiple friction loss estimation methods for robust pipeline design and validation. From these estimated pumping heads for different climate risk models, we can effectively accommodate even the worst-case scenarios to ensure cosntant water supply for the recipient Mananga basin.

3.4 Pump Modelling and Optimization

Three pump models were identified and simulated based on the water transfer flowrate and head requirements. Flowserve DMX (max head: 600 m, max flow:5000 m^3/h); KSB Omega 300-700 (max head: 200 m, max flow:2000 m^3/h and Grundfos CRN 185-6 (head: 253.8 m, flow: 251.9 m^3/h). Pump layouts for each pump model is visualized in Figure 4 for all scenarios. These layouts were optimized by ensuring pumping heads are satisfied across the segemnt while prioritizing upstream pump placement, proactively mitigating hydraulic risks associated with cavitation and maintaining pipeline integrity and avoiding subsea pumping for ease of pumping maintenance and infrastructure installment. Such strategic upstream placement aligns closely with global best practices for pipeline systems, which emphasize early pressure management to prevent operational disruptions due to negative pressures and cavitation.[58,59]

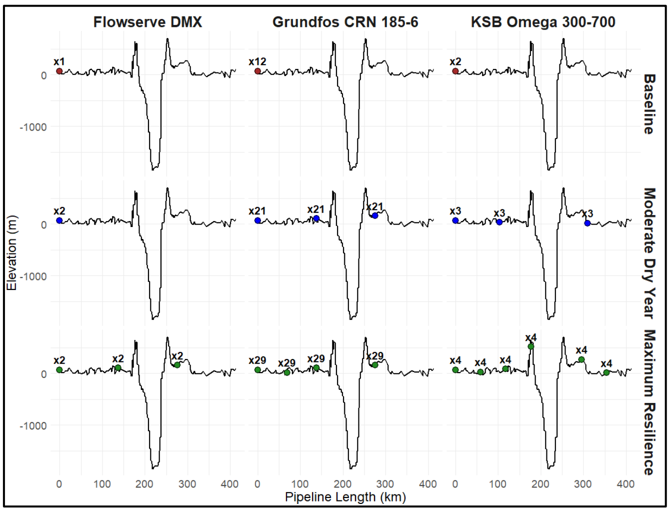


Figure 4. Elevation profiles of pipeline showing optimized pump station layouts (in dots) for three pump models for different scenarios.

Under baseline conditions, the pump infrastructure remained minimal, requiring only one to two pump stations regardless of pump model, reflecting similar findings in established water transfer projects like the Lesotho Highlands Water Project in Southern Africa, where moderate flow conditions similarly necessitated minimal pumping infrastructure.[60] However, scenarios designed for more demanding conditions, such as Moderate Dry Year and Maximum Resilience, required significantly increased numbers of pump stations. For instance, the smaller-capacity Grundfos pumps required up to 29 parallel installations, contrasting sharply with the fewer stations needed for larger-capacity KSB Omega and Flowserve DMX pumps. This result underscores the significant implications of pump selection on system complexity, operational cost, and reliability as emphasized in industry standards on pipeline optimization and pump station design[61,62]. Among the three evaluated pump models, the Flowserve DMX emerged as the optimal configuration, consistently requiring the fewest pump stations across all scenarios, even under the most demanding operational conditions.The reduced number of pump stations directly translates into substantial advantages, including lower infrastructure complexity, reduced capital and operational expenditures, simplified maintenance schedules, and increased overall reliability.

Moreover, this clear advantage aligns with best practices observed in major global pipeline projects, where fewer, larger-capacity pumping stations generally enhance operational efficiency, sustainability, and reliability.[63,64] Consequently, the Flowserve DMX configuration represents the most strategically advantageous solution, effectively balancing infrastructure feasibility, cost-efficiency, and long-term operational resilience for this inter-basin water transfer system.

Figure 5 shows the pressure profile of the pipeline after installing the Flowserve DMX, confirming that pressure requirements are met with the current pump layout. However, the maximum internal pressure reaches approximately 2000 m of head (~19.62 MPa), which exceeds the limits of standard HDPE (e.g., PE100 SDR11). To retain HDPE for its corrosion resistance and flexibility, reinforced or custom thick-walled variants can be used along with smart point sensors at specified distances to monitor pressure and detect leaks to ensure monitoring, consistent flow, and structural integrity under high pressure, in line with ISO 4427 and American Water Works Association M55 design standards.[82]

3.5 Project Costs

The lifecycle economic assessment revealed varied cost profiles across the three pump configurations, as illustrated in Figure 6. The Flowserve DMX model had the lowest pump procurement cost at ₱38.52 million (USD 0.70 million), followed by KSB Omega 300-700 at ₱59.92 million (USD 1.09 million), and Grundfos CRN 185-6 at ₱744.72 million (USD 13.54 million). When broader infrastructure components such as pipeline installation, civil works, land acquisition, electrical systems, and contingencies were incorporated and discounted to present value, total capital expenditure (CAPEX) rose to ₱0.74 billion (USD 13.5 million) for Flowserve, ₱1.14 billion (USD 20.7 million) for KSB, and ₱14.2 billion (USD 258.2 million) for Grundfos. These distributions align with cost structures observed in national projects like the Balog-Balog Multipurpose Project Phase II, where pipelines and civil works often account for 70–85% of total investment[65,66].

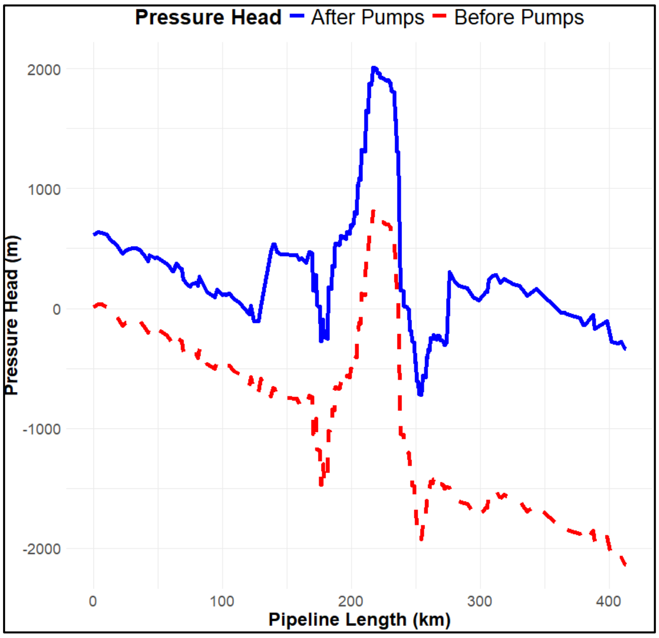


Figure 5. Pressure head profile along the pipeline before and after pump installation.

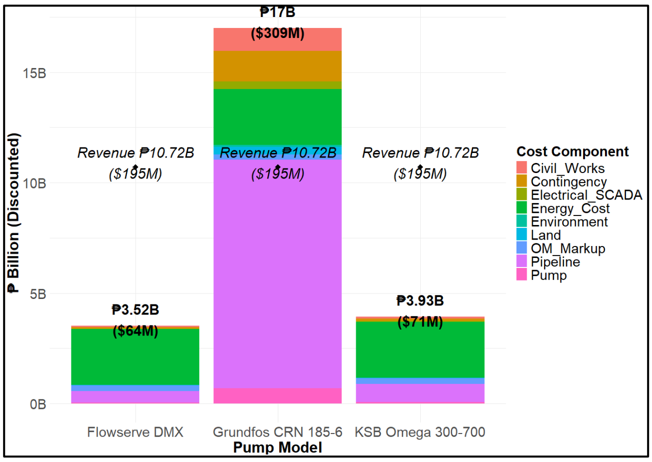


Figure 6. Lifecycle cost breakdown and revenue comparison for three pump models.

Operational expenditures (OPEX), including discounted energy costs and a 10% maintenance markup, were computed over a 20-year period using a 4% annual energy price escalation and an 8% discount rate. OPEX was held constant at ₱2.78 billion (USD 50.5 million) across all configurations due to uniform hydraulic conditions and power demand. Consequently, total lifecycle costs (CAPEX + OPEX) were ₱3.52 billion (USD 64 million) for Flowserve, ₱3.93 billion

(USD 71 million) for KSB, and ₱17 billion (USD 309 million) for Grundfos. When compared against projected NPV revenues of ₱10.72 billion (USD 195 million), Flowserve achieved the most favorable benefit–cost ratio (BCR) at 3.04, followed by KSB at 2.72, while Grundfos yielded a significantly lower BCR of 0.63. These findings highlight the economic advantage of right-sized systems with optimized capital allocation, supporting the Philippine Water Supply and Sanitation Master Plan's emphasis on lifecycle-based investment strategies.[67]. However, it is worth noting that risk mitigation and optimization strategies for long-term project sustainability would still change these projected values.

3.6 Risk Mitigation Strategies and Water Transfer Optimization

The Risk Register (S.3) shows 14 key risks identified through semi-quantitative risk assessment focusing on environmental, economic, and social dimensions based on government reports and other comparable projects.[32-56] Environmental risks are the most dominant category including geohazard-related threats such as seismic pipeline rupture, typhoon-related damage, and volcanic activity due to country's high exposure to natural hazards. Economic vulnerabilities such as energy supply disruption and pump system failure also scored high due to the remote and energy-intensive nature of long-distance water transfer. Social risks, including public opposition, land access disputes, and armed conflict, ranked critical in terms of reputational and permitting risks, further emphasizing the need for robust stakeholder engagement.

It is also worth noting that the The Agusan River is classified as Class A, with BOD levels below 5 mg/L and acceptable nitrate levels, requiring only conventional treatment, which is already standard practice among Philippine water utilities, removing the need for mitigation strategies regarding water quality.

Mitigation strategies were identified for each risk and their corresponding implementation cost estimate, expressed as a percentage of total project budget referencing with similar projects.[32-56] Seismic mitigation strategies were costed at approximately 2.5% of total cost. Typhoon resilience measures, including wind-resistant design and emergency shutdown plans, were among the most expensive at 3.5%, while marine ecosystem protections such as trenchless installation and seasonal routing were projected at 4.0%. Community engagement programs were comparatively lower in cost, estimated between 1.5–2.0%, but important in mitigating delays and gaining local support.

The results underscore the necessity of early and integrated risk mitigation, particularly for critical environmental and social risks. Without targeted interventions, risks remain high, posing threats to infrastructure performance, social acceptance, and environmental compliance. Embedding these strategies into the project's optimisation and economic model ensures that risk management is not treated as a reactive process but rather as a foundational element of planning. This integrated approach supports long-term operational continuity, financial resilience, and public trust key for sustainable and adaptive water infrastructure development in hazard-prone contexts like the Philippines.

3.7 Project Impacts

This interbasin pipeline project is anticipated to deliver substantial social benefits, particularly in addressing Cebu's persistent water scarcity. By increasing water availability by approximately 58.26 liters per capita per day (LPCD), the system could meet nearly 39% of Cebu's daily demand, significantly enhancing supply security for residential, agricultural, and industrial sectors. This improvement aligns with findings from the Chao Phraya River Basin in Thailand, where water resource developments have significantly augmented water availability during dry seasons.[79] Beyond water supply, the project is expected to generate notable socioeconomic benefits. It is projected to create 639 jobs during construction and sustain 142 operational roles. This is particularly impactful in regional areas where such opportunities are limited, and the economic ripple effects through local supply chains and services further reinforce its role in driving inclusive development.

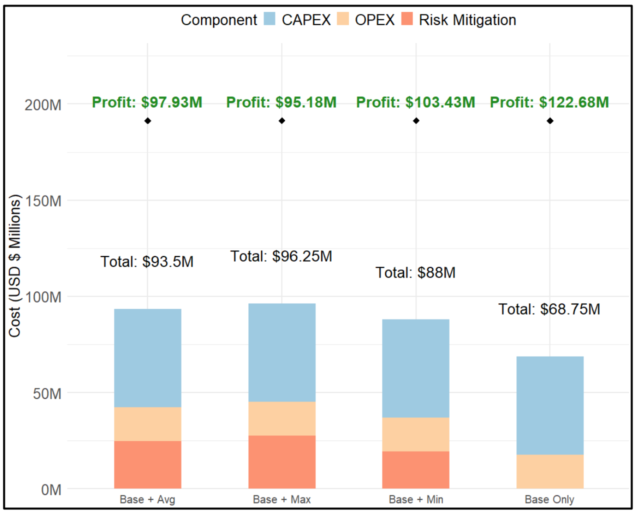


Figure 7. Lifecycle cost breakdown and profit under different risk scenarios for Flowserve DMX in USD.

Financially, the project demonstrates strong viability across all risk-adjusted scenarios as shown in Figure 7. Even under maximum risk mitigation, total discounted costs remain well below the projected NPV revenue of USD 194.61 million (₱10.72 billion), with profits ranging from USD 95.18 million

(₱5.33 billion) to USD 122.68 million (₱6.87 billion). The Base Only scenario yields the highest return but excludes crucial resilience measures. In contrast, the Base + Minimum and Base + Average scenarios offer a more strategic balance, achieving profits of USD 103.43 million (₱5.79 billion) and USD 97.93 million (₱5.49 billion) respectively, while incorporating seismic, climate, environmental, and social safeguards. These results support global recommendations to allocate 10.0–40.0% of infrastructure budgets to risk management in hazard-prone regions, ensuring long-term system reliability and sustainability.

Lastly, annual carbon emissions from pumping operations are estimated at 14.85 tons CO_2, but could be reduced to 0.51 tons if powered entirely by hydroelectric energy, which is already currently being generated in the Wawa Dam for Agusan River[84], making it a viable option. Incorporating renewable energy into the system aligns with low-carbon development goals and the Asian Development Bank's guidance for climate-resilient infrastructure, which encourages energy transition and emission minimization across the water sector. Marine ecosystem disruption during construction is projected to be limited to a seabed disturbance area of 0.1 km^2, primarily associated with trenching and pipe-laying. While the physical footprint is small, localized ecological impacts such as sedimentation, turbidity, and habitat alteration remain a concern. Similar studies on offshore infrastructure have shown that even minimal seabed disturbance can trigger benthic community shifts if unmitigated.[80] To reduce risk, best practices recommend timing activities to avoid breeding seasons, deploying silt curtains, and conducting post-installation monitoring.[81]

Most importantly, the project addresses drought-related risks in Cebu through reliable water supply, while simultaneously mitigating flood risks in the Agusan Basin caused by water oversupply, thereby underscoring the comprehensive benefits of this IBWT initiative.

4. Conclusion and Recommendations

This study evaluated the feasibility of an inter-basin water transfer (IBWT) system between Agusan and Mananga river basins in the Philippines to address the significant challenges of water scarcity and flood management between these regions, respectively. The proposed project has shown potential to enhance water availability in a water-scarce region while managing flood risks in a flood-prone area, underscoring economic viability and aligning with global sustainability objectives by significantly reducing CO_2 emissions. The technical and strategic planning and hydraulic modeling and geospatial analysis also provided a scalable framework for addressing regional water imbalances through infrastructural development. This project shows advancement towards achieving long-term water security and climate-resilient infrastructure development within an archipelagic country.

While potentially augmenting water scarcity needs of Cebu, it is also worth pointing out that the diverted water from Agusan although can reduce river and urban floodings, only amounts to 1.37%, leaving a significant portion of the excess water that can still leave Agusan flood-prone. However, this significant amount of water from Agusan also provides an opportunity to solve water scarcity problems in other regions, or even countries. Moroever, further refinement of the IBWT system's design and operation is imperative to ensure its effectiveness and sustainability. Detailed engineering should extend to the incorporation of specific pipeline components such as fittings and instrumentation to enhance the precision of hydraulic and cost models. Up-to-date vendor quotations are crucial for validating the estimated capital and operational expenditures. Additionally, conducting a comprehensive Environmental Impact Assessment, focusing on site-specific marine biodiversity, is recommended to thoroughly evaluate potential ecological impacts and develop corresponding mitigation strategies. To foster community acceptance and regulatory alignment, proactive and continuous stakeholder engagement should be prioritized. These steps will not only refine the project's operational integrity but also strengthen its social acceptability, ensuring that the IBWT system can effectively meet the objectives of enhancing regional water security and sustainability in the Philippines.

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References

1. United Nations Educational, Scientific and Cultural Organization (UNESCO). *UN World Water Development Report 2019: Leaving No One Behind*. United Nations Educational, Scientific and Cultural Organization, https://www.unwater.org/publications/un-world-water-development-report-2019.
2. Zhang, Q. The South-to-North Water Transfer Project of China: Environmental Implications and Monitoring

Strategy1. *JAWRA Journal of the American Water Resources Association* **45**, 1238–1247 (2009).
3. National Economic and Development Authority (NEDA). *Updated Philippine Development Plan 2017-2022*. National Economic and Development Authority, 2021.
4. Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). *Tropical Cyclone Information*. Department of Science and Technology, https://www.pagasa.dost.gov.ph/climate/tropical-cyclone-information.
5. Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). *Climate of the Philippines*. Department of Science and Technology, https://www.pagasa.dost.gov.ph/information/climate-philippines.
6. National Irrigation Administration (NIA). *Magat Dam Opens Gates Due to Typhoon Ulysses*. National Irrigation Administration, https://www.nia.gov.ph/content/magat-dam-opens-gates-due-typhoon-ulysses.
7. Porio, E., Dator Bercilla, J., Narisma, G., Cruz, F. & Yulo-Loyzaga, A. Drought and Urbanization: The Case of the Philippines: Methods, Approaches and Practices. in 183–208 (2019). doi:10.1007/978-981-10-8947-3_12.
8. Food and Agriculture Organization (FAO). *2015–2016 El Niño*. https://openknowledge.fao.org/server/api/core/bitstreams/a80370e6-1845-4c16-aa6f-0b817b99032f/content.
9. Lapong, E. & Fujihara, M. Water Resources in the Philippines : An Overview of its Uses, Management, Problems and Prospects. *Journal of Rainwater Catchment Systems* **14**, 57–67 (2008).
10. Gupta, J. & van der Zaag, P. Interbasin water transfers and integrated water resources management: Where engineering, science and politics interlock. *Physics and Chemistry of the Earth, Parts A/B/C* **33**, 28–40 (2008).
11. Kibiiy, J. & Ndambuki, J. M. New criteria to assess interbasin water transfers and a case for Nzoia-Suam/Turkwel in Kenya. Physics and Chemistry of the Earth, Parts A/B/C 89-90, 121–126 (2015).
12. The World Bank Group. World Bank Climate Change Knowledge Portal. climateknowledgeportal.worldbank.org https://climateknowledgeportal.worldbank.org/country/philippines/climate-data-historical (2021).
13. Global Facility for Disaster Reduction and Recovery (GFDRR). Think Hazard. www.thinkhazard.org https://www.thinkhazard.org/en/ (2020).
14. Philippine Institute of Volcanology and Seismology. Hazard Maps. www.phivolcs.dost.gov.ph https://www.phivolcs.dost.gov.ph/index.php/gisweb-hazard-maps.
15. UNEP-WCMC. *Protected Area Profile for Philippines from the World Database on Protected Areas, April 2025*. www.protectedplanet.net (2025)
16. Nishikawa, G., Yuichi Shiohama, Suzuki, T., Onuma, H. & Junji Kiyono. Evaluation On Seismic Performance Of Water Supply Equipment Using High Density Polyethylene Pipe. Journal of Japan Society of Civil Engineers Ser A1 (Structural Engineering & Earthquake Engineering (SE/EE)) 74, I_1002–I_1009 (2018).
17. Kim, S. Maximum allowable fluid velocity and concern on piping stability of ITER Tokamak cooling water system. Fusion Engineering and Design 162, 112049 (2021).
18. United States Environmental Protection Agency. Wastewater Technology Fact Sheet Sewers, Force Main. https://www3.epa.gov/npdes/pubs/force_main_sewers.pdf (2000).
19. Hosam El-Din M. Moghazi. Estimating Hazen-Williams Coefficient for Polyethylene Pipes. Journal of Transportation Engineering 124, 197–199 (1998).
20. Krimpenfort , H. A comparison between various pump systems for high flow rate tailings pipelines. papers.acg.uwa.edu.au 155–168 https://papers.acg.uwa.edu.au/p/1805_12_Krimpenfort/ (2018).
21. Manila Electric Company (Meralco). *June 2023 Rates Update*. https://company.meralco.com.ph/news-and-advisories/june-2023-rates-updates (accessed April 2025).
22. World Bank. Benchmarking Infrastructure Development 2023 – Philippines PPP Framework. https://bpp.worldbank.org/content/dam/sites/data/bpp/cntrypdf/BI-2023-Philippines-PPP.pdf (accessed April 2025).
23. Piquero, P. MCWD adjusts rates: Why water bill may be lower, higher this March. *Cebu Daily News* https://cebudailynews.inquirer.net/627480/mcwd-adjusts-rates-why-water-bill-may-be-lower-higher-this-march (2025).
24. Hong, J., Agustin, W., Yoon, S. & Park, J.-S. Changes of extreme precipitation in the Philippines, projected from the CMIP6 multi-model ensemble. Weather and Climate Extremes 37, 100480 (2022). https://doi.org/https://doi.org/10.1016/j.wace.2022.100480
25. National Economic and Development Authority (NEDA). Philippine Water Supply and Sanitation Master Plan. Government of the Philippines. (2019).
26. Talavera, S. J. Vivant targets 2025 launch for Cebu desalination plant. BusinessWorld Online (2025).
27. Durmaz, A., Ünal, E. & Aydın, C. Automatic Pipeline Route Design with Multi-Criteria Evaluation Based on Least-Cost Path Analysis and Line-Based Cartographic Simplification: A Case Study of the Mus Project in Turkey. ISPRS International Journal of Geo-Information 8, 173 (2019).
28. Candido, L., Coêlho, G., Alcoforado de Moraes, M. & Florencio, L. State-of-the-Art Review Review of Decision Support Systems and Allocation Models for Integrated Water Resources Management Focusing on Joint Water Quantity-Quality. Journal of Water Resources Planning and Management 148 (2021). https://doi.org/10.1061/(ASCE)WR.1943-5452.0001496
29. Rollason, E., Sinha, P. & Bracken, L. J. Interbasin water transfer in a changing world: A new conceptual model. Prog. Phys. Geogr. 45, 1–27 (2021). https://doi.org/10.1177/03091333211065004.
30. Blackmore, J. et al. Risk assessment and management: a guide for integrated urban water systems.

31. World Bank & Asian Development Bank. Infrastructure for a Seamless Asia. (ADB, 2019).
32. International Energy Agency (IEA). World Energy Outlook 2021. (IEA, 2021).
33. UN Water. Policy Brief: Water and Climate Change. (United Nations, 2020).
34. International Finance Corporation (IFC). Environmental and Social Risk Management. (IFC, 2020).
35. WSP Global. Security Planning for Linear Infrastructure Projects. (WSP, 2017).
36. United States Environmental Protection Agency (EPA). Corrosion Control Technical Assistance Manual. (EPA, 2016).
37. Water Research Foundation. Asset Management Practices and Tools for Water Utilities. (WRF, 2018).
38. National Oceanic and Atmospheric Administration (NOAA). Environmental Sensitivity Index Guidelines. (NOAA, 2019).
39. United Nations Environment Programme (UNEP). Marine Ecosystem Impact Assessment Guidelines. (UNEP, 2017).
40. United States Geological Survey (USGS). Earthquake Hazards Program: Pipeline Safety. (USGS, 2018).
41. Japan International Cooperation Agency (JICA). Infrastructure Risk Management Manual. (JICA, 2016).
42. GNS Science. Volcanic Hazard Assessments in the Philippines. (GNS, 2015).
43. United Nations Office for Disaster Risk Reduction (UNDRR). Global Assessment Report on Disaster Risk Reduction 2021. (UNDRR, 2021).
44. Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). Typhoon Risk Atlas of the Philippines. (PAGASA, 2020).
45. World Bank. Building Back Better from Typhoon Haiyan: A Planning Guide. (WB, 2019).
46. Hamid-Mosaku, I. A., Oguntade, O. F., Ifeanyi, V. I., Balogun, A.-L. & Jimoh, O. A. Evolving a comprehensive geomatics multi-criteria evaluation index model for optimal pipeline route selection. *Struct. Infrastruct. Eng.* **17**, 1–14 (2020).
47. World Meteorological Organization (WMO). Ash Dispersal Forecasting and Volcanic Impact on Water Infrastructure. (WMO, 2021).
48. World Health Organization (WHO). Guidelines for Drinking-Water Quality, 4th ed. (WHO, 2021).
49. International Water Management Institute (IWMI). Water Quality and Health: Urban and Peri-Urban Agriculture. (IWMI, 2018).
50. Global Water Partnership (GWP). Integrated Water Resources Management Guidelines. (GWP, 2019).
51. United Nations Development Programme (UNDP). Guidelines on Free, Prior and Informed Consent (FPIC). (UNDP, 2016).
52. Food and Agriculture Organization (FAO). Land Tenure and Development Framework. (FAO, 2019).
53. Asian Development Bank (ADB). Strengthening Participation for Development Results. (ADB, 2018).
54. United Nations Office on Drugs and Crime (UNODC). Infrastructure Protection in Conflict Zones. (UNODC, 2020).
55. International Committee of the Red Cross (ICRC). Guidelines for Critical Infrastructure in Conflict Settings. (ICRC, 2019).
56. Gyabeng, B. A. Selection of optimum petroleum pipeline routes using a multi-criteria decision analysis and GIS least-cost path approach. *Int. J. Sci. Res. Publ.* **10**, 572–579 (2020).
57. Walski, T. M., Chase, D. V., Savic, D. A., Grayman, W., Beckwith, S. & Koelle, E. Advanced Water Distribution Modeling and Management. (Haestad Press, 2003).
58. Swamee, P. K. & Sharma, A. K. Design of Water Supply Pipe Networks. (John Wiley & Sons, 2008).
59. Lesotho Highlands Development Authority. Lesotho Highlands Water Project. www.lhda.org.ls https://www.lhda.org.ls/.
60. Applied Flow Technology. Optimizing Pumping Systems to Minimize First or Life-Cycle Costs. (AFT, 2020). Available at: https://www.aft.com/documents/AFT-Optimizing-Pumping-Systems.pdf
61. Moura, L., Lopes, M. A., Lima, R. & Martins, A. Methodology for pumping station design based on analytic hierarchy process. Water 13, 2886 (2021).
62. Zhang, L., Chen, Y., & Ahmed, S. Challenges for pumping station design in water industries: A review. Water Res. 254, 120052 (2024).
63. Hunt, S. Four considerations for large pump station design. Water & Wastes Digest (2023). Available at: https://www.wwdmag.com/collection-systems/article/33019631/four-considerations-for-large-pump-station-design
64. INQUIRER.net. NIA taps contractors for P5.8-B dam project. INQUIRER.net https://business.inquirer.net/230209/nia-taps-contractors-p5-8-b-dam-project?utm_source=chatgpt.com (2017).
65. Salazar, J. & Project. Strategic lnitiatives Profile (Annex C) NATIONAL IRRIGATION ADMINISTRATION STRATEGIC INITIATIVES PROFILE l. Srnerecrc lnrrrrilve PnorLe I 1. Name of Project: Balog-Balog Multipurpose Project Phase ll (BBMP ll) 2. Project Team: Engr. Florencio F. Padernal, DPA, NIA Administrator Activities Timeline Budget. https://www.nia.gov.ph/sites/default/files/pdf_reader/2016-PES_Form_2.pdf (2016).
66. National Economic and Development Authority. Philippine Water Supply and Sanitation Master Plan. *The National Economic and Development Authority* https://neda.gov.ph/pwssmp/ (2021).
67. Asian Development Bank . Guidelines for the Economic Analysis of Projects. https://www.adb.org/sites/default/files/institutional-document/32256/economic-analysis-projects.pdf?utm_source=chatgpt.com (2017).
68. Iqbal, M. PROBABILITY AND IMPACT MATRIX : PMP/CAPM. Mudassir Iqbal https://mudassiriqbal.net/probability-and-impact-matrix/ (2023).
69. Lienert, J., Scholten, L., Egger, C. & Maurer, M. Structured decision-making for sustainable water infrastructure planning and four future scenarios. EURO Journal on Decision Processes 3, 107–140 (2015).
70. US Water Alliance. The economic benefits of investing in water infrastructure. *US Water Alliance* (2023). Available at: https://uswateralliance.org/wp-content/uploads/2023/09/Economic-Impact-of-Investing-in-Water-Infrastructure_VOW_FINAL_pages_0.pdf
71. Water Environment Research Foundation. National economic and labor impacts of the water utility sector.

WERF (2014). Available at: https://cdcauthority.org/WERF%20Economic%20Impact%20Full%20Report.pdf
72. NOAA National Centers for Environmental Information. Billion-Dollar Weather and Climate Disasters: 2012 Drought and Heatwave. Natl. Oceanic Atmos. Adm. https://www.ncei.noaa.gov/access/billions/events/US/1980-2022?disasters[]=drought&eventType=Drought&startDate=2012-01-01&endDate=2012-12-31&filters=eventType (2013).
73. Department of Energy (DOE). 2015–2017 National Grid Emission Factor (NGEF). https://www.doe.gov.ph/electric-power/2015-2017-national-grid-emission-factor-ngef (2018).
74. International Hydropower Association. International Hydropower Association. www.hydropower.org https://www.hydropower.org/factsheets/greenhouse-gas-emissions (2022).
75. Japan International Cooperation Agency (JICA). Data Collection Survey for National Water Resources Development and Management Plan Final Report Annex-D-Hydrology. https://openjicareport.jica.go.jp/pdf/12383972_05.pdf (2023).
76. Asian Development Bank. Philippines: Master Plan for the Agusan River Basin. https://www.adb.org/sites/default/files/project-documents//36540-phi-tacr.pdf (2008).
77. Swamee, P. K. & Sharma, A. K. *Design of Water Supply Pipe Networks*. (John Wiley & Sons, 2008). https://doi.org/10.1002/9780470225059
78. Chadwick, A., Morfett, J. & Borthwick, M. *Hydraulics in Civil and Environmental Engineering*. 5th edn, (CRC Press, 2013). https://doi.org/10.1201/b16398
79. Molle, F. & Floch, P. The adaptive irrigation system of the Chao Phraya Delta in Thailand. Irrig. Drain. Syst. 22, 135–157 (2008). Available at: https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers19-02/010047106.pdf
80. Erftemeijer, P. L. A. & Lewis, R. R. Environmental impacts of dredging on seagrasses: A review. Mar. Pollut. Bull. 52, 1553–1572 (2006). https://doi.org/10.1016/j.marpolbul.2006.09.006
81. NOAA. Best Management Practices for Offshore Marine Construction: Protecting Water Quality and Habitat. U.S. National Oceanic and Atmospheric Administration (2015). https://repository.library.noaa.gov/view/noaa/19833
82. American Water Works Association. M55: PE Pipe—Design and Installation, 2nd edn (American Water Works Association, 2020); https://store.awwa.org/M55-PE-Pipe-Design-and-Installation-Second-Edition
83. Department of Environment and Natural Resources (DENR). Water Quality Guidelines and General Effluent Standards of 2016 (DAO 2016-08) (DENR, 2016).
84. Japan International Cooperation Agency. Wawa River Small Hydro Power Project. *Jica.go.jp* https://www.jica.go.jp/english/about/policy/environment/id/asia/southeast/a_b_fi/philippines/c8h0vm00009664kj.html (2025).

SUPPLEMENTARY INFORMATION

1. WATER SUITABILITY SCORES FOR EACH PHILIPPINE REGION

2. HYDRAULIC MODELLING EQUATIONS

a. Darcy-Weisbach Equation

$$h_f = \frac{fLDv^2}{2g}$$

b. Hazen-Williams Equation

$$h_f = \frac{10.67LQ^{1.852}}{C^{1.852}D^{4.87}}$$

c. Bernoulli's Equation

$$h_p = \Delta z + h_f + h_f + \Delta P$$

3. RISK REGISTER

Category	Risk Title	Cause	Event	Consequence	Likelihood (L)	Impact (I)	Risk Rating (LxI)	Risk Level	Mitigation Strategy	Estimated cost (% of Project Cost)	Source
Economic	Pump & pressure system failure	Poor pressure modeling and lack of redundancy	Mechanical failure and system downtime	Operational inefficiency and higher O&M costs	3	4	12	High	Install backup systems, real-time pressure monitoring	2.0%	32
Economic	Energy supply disruption	Single-source energy dependence, power grid instability	Pump shutdown or inconsistent operations	Interrupted water transfer schedule	4	4	16	Critical	Use hybrid energy sources and backup generators	3.0%	33, 34
Economic	Sabotage, terrorism or vandalism	Inadequate physical security or surveillance	Pipeline breach, contamination, or flow interruption	Water delivery disruption; public health risk; costly repairs	2	4	8	Medium	Deploy surveillance systems; fencing; community security partnerships	1.0%	35, 36
Economic	Corrosion and pipe degradation	Long exposure to moist, salty, or acidic environments	Pipe thinning or leakage	Reduced pipeline life; leakage; environmental damage	3	4	12	High	Protective coatings, corrosion monitoring and maintenance schedule	1.5%	37, 38
Environment	Marine ecosystem disruption	Pipeline routing through marine ecosystems	Damage to marine habitats, license violation	Regulatory penalties and project stoppage	3	5	15	High	Avoid critical habitats, schedule around ecological cycles	4.0%	39, 40
Environment	Seismic pipeline rupture	Pipeline crosses active fault lines	Pipeline rupture during seismic event	System failure and water delivery interruption	5	5	25	Critical	Seismic-resistant design, route monitoring	2.5%	41, 42
Environment	Volcanic eruption impact	Pipeline traverses volcanic region	Flow interruption, burial, or	Severe damage or full system disruption	3	5	15	High	Avoid high-risk volcano zones; remote	1.2%	43, 44

Category	Risk Title	Cause	Event	Consequence	Likelihood (L)	Impact (I)	Risk Rating (LxI)	Risk Level	Mitigation Strategy	Estimated cost (% of Project Cost)	Source
			pyroclastic damage						shut-off protocols		
Environment	Typhoon-related damage	Pipeline exposed to extreme weather	Infrastructure damage and service disruption	Infrastructure destruction; prolonged recovery	5	5	25	Critical	Wind-resistant design; emergency shut-off planning	3.5%	45, 46
Environment	Volcano-triggered ash blockage	Ashfall entering intake or pump systems	Blockage or pump failure due to ash accumulation	Sudden shutdown; water quality hazard	3	4	12	High	Volcano monitoring; backup intakes; ash-resistant filters	0.8%	41, 48
Environment	Water quality degradation	Contamination during transfer	Degraded water at recipient basin	Public health risk; increased treatment costs	3	3	9	Medium	Real-time water quality monitoring; filters; emergency shut-offs; Availability of conventional water treatment	2.0%	49, 50
Environment	Wastewater discharge mismanagement	Lack of integrated water-wastewater planning	Discharge into receiving bodies or land	Contamination; health risk; reputational/legal issues	3	4	12	High	Treated wastewater reuse; IWRM integration; continuous monitoring	2.5%	34, 51
Social	Land access dispute	Unclear land ownership; poor stakeholder engagement	Community resistance and legal delays	Project delay; reputational damage	4	4	16	Critical	Early community engagement; land use agreements	2.0%	52, 53
Social	Public opposition	Inadequate consultation and poor communication	Loss of LGU/community support	Permitting delays; reputational impact	4	4	16	Critical	Community engagement; grievance	1.8%	54

Category	Risk Title	Cause	Event	Consequence	Likelihood (L)	Impact (I)	Risk Rating (LxI)	Risk Level	Mitigation Strategy	Estimated cost (% of Project Cost)	Source
									redress mechanisms		
Social	Terrorism or armed conflict	Route crosses conflict-prone zones	Restricted access; potential violence	Service halt; staff risk; regional instability	2	5	10	Medium	Avoidance in planning; coordination with security forces	1.0%	55, 56

4. R CODES

A. Rainfall Heat Map

```
library(sf)         # For spatial data
library(ggplot2)    # For visualization
library(dplyr)      # For data manipulation
library(readxl)     # For reading Excel files

# -----------------------------
# Load Province-Level Shapefile
# -----------------------------
shapefile_path <- "D:\\USYD\\Advanced Industrial Modelling\\Project
1\\Shapefiles\\phl_admbnda_adm2_psa_namria_20231106.shp"

# Read the shapefile
provinces <- st_read(shapefile_path)

# Check CRS and transform if necessary
if (st_crs(provinces)$epsg != 4326) {
  provinces <- st_transform(provinces, crs = 4326)
}

# -----------------------------
# Load Precipitation Data
# -----------------------------
rainfall_file <- "D:\\USYD\\Advanced Industrial Modelling\\Project 1\\Regional Data.xlsx"
rainfall_data <- read_excel(rainfall_file)

# Rename the correct column to "Province" if needed
colnames(rainfall_data)  # Run this to check actual column names

rainfall_data <- rainfall_data %>%
  rename(Province = `Province...1`)  # Adjust based on actual column name

# -----------------------------
# Merge Precipitation Data with Province Shapefile
# -----------------------------
provincial_map_data <- provinces %>%
  left_join(rainfall_data, by = c("ADM2_EN" = "Province"))  # Match provinces

# -----------------------------
# Remove NA and Simplify Geometries
# -----------------------------
provincial_map_data <- provincial_map_data %>% filter(!is.na(`Average rainfall`))
provincial_map_data$geometry <- st_simplify(provincial_map_data$geometry, dTolerance = 0.01)

# -----------------------------
# Close Open Graphics Devices to Avoid Errors
# -----------------------------
```

```
graphics.off()

# -----------------------------
# Generate the Precipitation Gradient Map
# -----------------------------
precipitation_map <- ggplot() +
  # Gradient map for all provinces
  geom_sf(data = provincial_map_data, aes(fill = `Average rainfall`), color = "black", size = 0.3) +

  # Blue gradient for rainfall levels
  scale_fill_gradient(low = "lightblue", high = "darkblue",
                      name = "Average Rainfall (mm)") +

  # Remove province labels by not including geom_sf_text()

  # Map Titles
  labs(
    title = "Provincial Precipitation Gradient Map",
    subtitle = "Colored Based on Average Rainfall (mm)",
    caption = "Data Source: Your Data Source Here"
  ) +

  theme_minimal()

# -----------------------------
# Save the Plot to File Instead of Printing
# -----------------------------
ggsave("D:/USYD/Advanced Industrial Modelling/Project 1/Maps/Precipitation_Gradient_Map.png",
       plot = precipitation_map, width = 10, height = 7, dpi = 400)

# -----------------------------
# Print the plot for debugging
# -----------------------------
print(precipitation_map)

# -----------------------------
# Final Message
# -----------------------------
cat("\n✅ Precipitation gradient map saved as 'Precipitation_Gradient_Map.png'. Check your working directory.\n")
```

B. Flooding Heat Maps

```
library(sf)        # For spatial data
library(ggplot2)   # For visualization
library(dplyr)     # For data manipulation
library(readxl)    # For reading Excel files

# -----------------------------
# Load Province-Level Shapefile
# -----------------------------
```

```r
shapefile_path <- "D:\\USYD\\Advanced Industrial Modelling\\Project 1\\Provincial Shapefiles\\OneDrive_1_3-12-
2025\\phl_admbnda_adm2_psa_namria_20231106.shp"
# Read the shapefile
provinces <- st_read(shapefile_path)

# Check CRS and transform if necessary
if (st_crs(provinces)$epsg != 4326) {
  provinces <- st_transform(provinces, crs = 4326)
}

# -----------------------------
# Load River Flooding Data
# -----------------------------
flooding_file <- "D:\\USYD\\Advanced Industrial Modelling\\Project 1\\Regional Data.xlsx"
flooding_data <- read_excel(flooding_file)

# Rename the correct column to "Province" if needed
colnames(flooding_data)  # Run this to check actual column names

flooding_data <- flooding_data %>%
  rename(Province = `Province...1`)  # Adjust based on actual column name

# -----------------------------
# Merge Flooding Data with Province Shapefile
# -----------------------------
provincial_map_data <- provinces %>%
  left_join(flooding_data, by = c("ADM2_EN" = "Province"))  # Match provinces

# -----------------------------
# Remove NA and Simplify Geometries
# -----------------------------
provincial_map_data <- provincial_map_data %>% filter(!is.na(`River Flood`))
provincial_map_data$geometry <- st_simplify(provincial_map_data$geometry, dTolerance = 0.01)

# -----------------------------
# Convert Flood Risk to Numeric for Gradient
# -----------------------------
provincial_map_data <- provincial_map_data %>%
  mutate(Flood_Risk_Score = as.numeric(factor(`River Flood`,
                                       levels = c("Very Low", "Low", "Medium", "High"),
                                       ordered = TRUE)))

# -----------------------------
# Close Open Graphics Devices to Avoid Errors
# -----------------------------
graphics.off()

# -----------------------------
# Generate the River Flooding Gradient Map
# -----------------------------
flooding_map <- ggplot() +
  # Gradient map for all provinces
  geom_sf(data = provincial_map_data, aes(fill = Flood_Risk_Score), color = "black", size = 0.5) +
```

```
  # Red gradient for flooding risk levels
  scale_fill_gradient(low = "lightpink", high = "darkred",
                      name = "Flooding Risk Level",
                      breaks = c(1, 2, 3, 4),
                      labels = c("Very Low", "Low", "Medium", "High")) +

  # Remove province labels by not including geom_sf_text()

  # Map Titles
  labs(
    title = "Provincial River Flooding Risk Gradient Map",
    subtitle = "Colored Based on River Flood Risk",
    caption = "Data Source: Your Data Source Here"
  ) +

  theme_minimal()

# -----------------------------
# Save the Plot to File Instead of Printing
# -----------------------------
ggsave("D:/USYD/Advanced Industrial Modelling/Project 1/Maps/Flooding_Gradient_Map.png",
       plot = flooding_map, width = 10, height = 7, dpi = 400)


# -----------------------------
# Print the plot for debugging
# -----------------------------
print(flooding_map)

# -----------------------------
# Final Message
# -----------------------------
cat("\n✅ River Flooding gradient map saved as 'River_Flooding_Gradient_Map.png'. Check your working directory.\n")
```

C. Water Scarcity Heat Map

```
library(sf)        # For spatial data
library(ggplot2)   # For visualization
library(dplyr)     # For data manipulation
library(readxl)    # For reading Excel files

# -----------------------------
```

```
# Load Province-Level Shapefile
# -----------------------------
shapefile_path <- "D:\\USYD\\Advanced Industrial Modelling\\Project 1\\Provincial Shapefiles\\OneDrive_1_3-12-2025\\phl_admbnda_adm2_psa_namria_20231106.shp"
# Read the shapefile
provinces <- st_read(shapefile_path)

# Check CRS and transform if necessary
if (st_crs(provinces)$epsg != 4326) {
  provinces <- st_transform(provinces, crs = 4326)
}

# -----------------------------
# Load Water Scarcity Data
# -----------------------------
scarcity_file <- "D:\\USYD\\Advanced Industrial Modelling\\Project 1\\Regional Data.xlsx"
scarcity_data <- read_excel(scarcity_file)

# Rename the correct column to "Province" if needed
colnames(scarcity_data)  # Run this to check actual column names

scarcity_data <- scarcity_data %>%
  rename(Province = `Province...1`)  # Adjust based on actual column name

# -----------------------------
# Merge Scarcity Data with Province Shapefile
# -----------------------------
provincial_map_data <- provinces %>%
  left_join(scarcity_data, by = c("ADM2_EN" = "Province"))  # Match provinces

# -----------------------------
# Remove NA and Simplify Geometries
# -----------------------------
provincial_map_data <- provincial_map_data %>% filter(!is.na(`Water scarcity`))
provincial_map_data$geometry <- st_simplify(provincial_map_data$geometry, dTolerance = 0.01)

# -----------------------------
# Convert Flood Risk to Numeric for Gradient
# -----------------------------
provincial_map_data <- provincial_map_data %>%
  mutate(Water_Scarcity_Score = as.numeric(factor(`Water scarcity`,
                                           levels = c("Very Low", "Low", "Medium", "High"),
                                           ordered = TRUE)))

# -----------------------------
# Close Open Graphics Devices to Avoid Errors
# -----------------------------
graphics.off()

# -----------------------------
# Generate the Water Scarcity Gradient Map
# -----------------------------
scarcity_map <- ggplot() +
```

```
 # Gradient map for all provinces
 geom_sf(data = provincial_map_data, aes(fill = Water_Scarcity_Score), color = "black", size = 0.3) +

 # Red gradient for flooding risk levels
 scale_fill_gradient(low = "wheat", high = "brown",
                     name = "Water Scarcity Rating",
                     breaks = c(1, 2, 3, 4),
                     labels = c("Very Low", "Low", "Medium", "High")) +

 # Remove province labels by not including geom_sf_text()

 # Map Titles
 labs(
   title = "Provincial Water Scarcity Rating Gradient Map",
   subtitle = "Colored Based on Water Scarcity",
   caption = "Data Source: Your Data Source Here"
 ) +

 theme_minimal()

# -----------------------------
# Save the Plot to File Instead of Printing
# -----------------------------
ggsave("D:/USYD/Advanced Industrial Modelling/Project 1/Maps/Scarcity_Gradient_Map.png",
       plot = scarcity_map, width = 10, height = 7, dpi = 400)


# -----------------------------
# Print the plot for debugging
# -----------------------------
print(scarcity_map)

# -----------------------------
# Final Message
# -----------------------------
cat("\n✅ River Flooding gradient map saved as 'RWater Scarcity aGdient_Map.png'. Check your working directory.\n")
```

D. Water Transfer Suitability Map

```
library(sf)        # For spatial data
library(ggplot2)   # For visualization
library(dplyr)     # For data manipulation
library(readxl)    # For reading Excel files

# -----------------------------
# Load Province-Level Shapefile
# -----------------------------
shapefile_path <- "D:\\USYD\\Advanced Industrial Modelling\\Project 1\\Provincial Shapefiles\\OneDrive_1_3-12-
2025\\phl_admbnda_adm2_psa_namria_20231106.shp"
provinces <- st_read(shapefile_path)

# Check CRS and transform if necessary
if (st_crs(provinces)$epsg != 4326) {
```

```
  provinces <- st_transform(provinces, crs = 4326)
}

# -----------------------------
# Load Water Transfer Suitability Data
# -----------------------------
suitability_file <- "D:\\USYD\\Advanced Industrial Modelling\\Project 1\\Regional Data.xlsx"
suitability_data <- read_excel(suitability_file)

# Check column names in Excel
colnames(suitability_data)

# Rename the correct column to "Final_Rating" if needed
suitability_data <- suitability_data %>%
  rename(Final_Rating = `Final Rating`,  # Replace with the real name
         Province = `Province...1`)  # Adjust based on colnames() output

# Ensure "Final Rating" is numeric
suitability_data <- suitability_data %>%
  mutate(Final_Rating = as.numeric(Final_Rating))

# Trim spaces to prevent merge issues
suitability_data$Province <- trimws(suitability_data$Province)
provinces$ADM2_EN <- trimws(provinces$ADM2_EN)

# -----------------------------
# Merge Suitability Data with Province Shapefile
# -----------------------------
provincial_map_data <- provinces %>%
  left_join(suitability_data, by = c("ADM2_EN" = "Province"))

# -----------------------------
# Check if merge was successful
# -----------------------------
if (sum(is.na(provincial_map_data$Final_Rating)) > 0) {
  warning("\n⚠ Some provinces did not match. Check for name mismatches between shapefile and Excel.")
}

# -----------------------------
# Remove NA and Simplify Geometries
# -----------------------------
provincial_map_data <- provincial_map_data %>% filter(!is.na(Final_Rating))
provincial_map_data$geometry <- st_simplify(provincial_map_data$geometry, dTolerance = 0.01)

# -----------------------------
# Close Open Graphics Devices to Avoid Errors
# -----------------------------
graphics.off()

# -----------------------------
# Generate the Water Transfer Suitability Gradient Map
# -----------------------------
suitability_map <- ggplot() +
```

```
  geom_sf(data = provincial_map_data, aes(fill = Final_Rating), color = "black", size = 0.3) +

  #  Gradient for Suitability
  scale_fill_gradient(low = "yellow", high = "darkgreen",
                      name = "Water Transfer Suitability",
                      breaks = range(provincial_map_data$Final_Rating, na.rm = TRUE),
                      labels = c("Most Suitable Recipient", "Most Suitable Donor")) +

  # Map Titles
  labs(
    title = "Provincial Water Transfer Suitability Gradient Map",
    subtitle = "From Most Suitable Recipient (Low) to Most Suitable Donor (High)",
    caption = "Data Source: Your Data Source Here"
  ) +

  theme_minimal()

# -----------------------------
# Ensure Maps Directory Exists Before Saving
# -----------------------------
output_directory <- "D:/USYD/Advanced Industrial Modelling/Project 1/Maps"

if (!dir.exists(output_directory)) {
  dir.create(output_directory, recursive = TRUE)  # Creates the folder if it doesn't exist
}

# Define full file path for saving
output_file <- file.path(output_directory, "Water_Transfer_Suitability_Map.png")

# -----------------------------
# Save the Plot to File Instead of Printing
# -----------------------------
ggsave(output_file,
       plot = suitability_map,
       width = 10,
       height = 7,
       dpi = 400)  # Increased DPI for higher resolution

# -----------------------------
# Print the plot for debugging
# -----------------------------
print(suitability_map)

# -----------------------------
# Final Message
# -----------------------------
cat("\n✅ Water Transfer Suitability map saved as:", output_file, "\n")
```

G. Pipeline Routing

```
# -----------------------------
# Load Required Libraries
# -----------------------------

library(sf)
library(ggplot2)
library(dplyr)
library(geosphere)
library(gridExtra)
library(grid)
library(osrm)
library(elevatr)
library(raster)
library(cowplot)     # For inset map

# -----------------------------
# Load Province-Level Shapefile
# -----------------------------
shapefile_path <- "D:/USYD/Advanced Industrial Modelling/Project 1/Provincial Shapefiles/OneDrive_1_3-12-
2025/phl_admbnda_adm2_psa_namria_20231106.shp"
provinces <- st_read(shapefile_path)
if (st_crs(provinces)$epsg != 4326) {
  provinces <- st_transform(provinces, crs = 4326)
}

# -----------------------------
# Load & Fix Protected Areas Shapefile
# -----------------------------
protected_areas_path <- "D:/USYD/Advanced Industrial Modelling/Project 1/PAs_under_NIPAS/PAs under
NIPAS/Protected_Areas_2022_Luzon1911_simple_attri.shp"
protected_areas <- st_read(protected_areas_path)
protected_areas <- st_transform(protected_areas, crs = st_crs(provinces))
protected_areas <- st_make_valid(protected_areas)
protected_areas <- st_simplify(protected_areas, dTolerance = 0.001)

# -----------------------------
# Load & Fix Fault Lines Shapefile
# -----------------------------
fault_lines_path <- "D:/USYD/Advanced Industrial Modelling/Project 1/Active_Faults/Active_Faults/Active_Faults.shp"
fault_lines <- st_read(fault_lines_path)
fault_lines <- st_transform(fault_lines, crs = st_crs(provinces))
fault_lines <- st_make_valid(fault_lines)
```

```
# -----------------------------
# Define Key Locations (Agusan & Cebu)
# -----------------------------
key_locations <- data.frame(
  Name = c("Agusan River Basin", "Mananga River Basin (Cebu)"),
  Lat = c(8.67, 10.29),
  Lon = c(125.58, 123.85)
)

source_sf <- st_as_sf(key_locations[1, ], coords = c("Lon", "Lat"), crs = 4326)
recipient_sf <- st_as_sf(key_locations[2, ], coords = c("Lon", "Lat"), crs = 4326)

# -----------------------------
# Define Pipeline Routes (Including Hybrid for Camiguin)
# -----------------------------
route1 <- gcIntermediate(c(125.58, 8.67), c(123.85, 10.29), n = 100, addStartEnd = TRUE, sp = FALSE)
route1_df <- as.data.frame(route1)
colnames(route1_df) <- c("Longitude", "Latitude")

route2 <- osrmRoute(src = source_sf, dst = recipient_sf, returnclass = "sf", overview = "full")
route2_df <- as.data.frame(st_coordinates(route2))
colnames(route2_df) <- c("Longitude", "Latitude")

# Camiguin Hybrid: Agusan -> Camiguin (OSRM), Camiguin -> Bohol (gcIntermediate), Bohol -> Cebu (OSRM)
waypoints3 <- data.frame(
  Lon = c(125.58, 124.72, 124.25, 123.85),
  Lat = c(8.67, 9.10, 9.88, 10.29)
)

# Agusan to Camiguin (Land)
seg1 <- osrmRoute(
  src = st_as_sf(waypoints3[1,], coords = c("Lon", "Lat"), crs = 4326),
  dst = st_as_sf(waypoints3[2,], coords = c("Lon", "Lat"), crs = 4326),
  returnclass = "sf"
)
seg1_df <- as.data.frame(st_coordinates(seg1))

# Camiguin to Bohol (Sea)
seg2 <- gcIntermediate(
  waypoints3[2, c("Lon", "Lat")],
  waypoints3[3, c("Lon", "Lat")],
  n = 200, addStartEnd = TRUE, sp = FALSE
)
seg2_df <- as.data.frame(seg2)
colnames(seg2_df) <- c("Longitude", "Latitude")

# Bohol to Cebu (Land)
seg3 <- osrmRoute(
  src = st_as_sf(waypoints3[3,], coords = c("Lon", "Lat"), crs = 4326),
  dst = st_as_sf(waypoints3[4,], coords = c("Lon", "Lat"), crs = 4326),
  returnclass = "sf"
)
```

```
seg3_df <- as.data.frame(st_coordinates(seg3))

colnames(seg1_df) <- colnames(seg3_df) <- c("Longitude", "Latitude")
route3_df <- bind_rows(seg1_df, seg2_df, seg3_df)

# -----------------------------
# Create Base Map and Inset Map
# -----------------------------
base_map <- ggplot() +
  geom_sf(data = provinces, fill = NA, color = "black", size = 0.3) +
  geom_sf(data = protected_areas, aes(fill = "Protected Areas"), alpha = 0.4, color = NA) +
  geom_sf(data = fault_lines, aes(color = "Fault Lines"), size = 1, linetype = "dotted", alpha = 0.8) +
  geom_path(data = route1_df, aes(x = Longitude, y = Latitude, color = "Direct Path"), size = 1.2) +
  geom_path(data = route2_df, aes(x = Longitude, y = Latitude, color = "Leyte Waypoint"), size = 1.2, linetype = "dashed") +
  geom_path(data = route3_df, aes(x = Longitude, y = Latitude, color = "Camiguin Waypoint"), size = 1.2, linetype =
"dotdash") +
  scale_color_manual(values = c(
    "Direct Path" = "red",
    "Leyte Waypoint" = "blue",
    "Camiguin Waypoint" = "green",
    "Fault Lines" = "purple"
  )) +
  scale_fill_manual(values = c("Protected Areas" = "darkgreen")) +
  labs(title = "Inter-basin Pipeline Routes across the Philippines") +
  theme_minimal() +
  theme(legend.position = "bottom")

# Inset map region (Visayas-Mindanao zoomed)
inset_map <- ggplot() +
  geom_sf(data = provinces, fill = NA, color = "black", size = 0.3) +
  geom_sf(data = protected_areas, fill = "darkgreen", alpha = 0.4, color = NA) +
  geom_sf(data = fault_lines, color = "purple", size = 1, linetype = "dotted", alpha = 0.8) +
  geom_path(data = route1_df, aes(x = Longitude, y = Latitude), color = "red", size = 1.2) +
  geom_path(data = route2_df, aes(x = Longitude, y = Latitude), color = "blue", size = 1.2, linetype = "dashed") +
  geom_path(data = route3_df, aes(x = Longitude, y = Latitude), color = "green", size = 1.2, linetype = "dotdash") +
  coord_sf(xlim = c(123, 126), ylim = c(8, 11)) +
  theme_void() +
  theme(panel.background = element_rect(fill = "white", color = "black", linewidth = 0.5))

# Combine with Inset (Top Right)
final_map <- ggdraw() +
  draw_plot(base_map) +
  draw_plot(inset_map, x = 0.60, y = 0.55, width = 0.38, height = 0.38)

ggsave("D:/USYD/Advanced Industrial Modelling/Project 1/Routing Maps/Pipeline_Map_with_Inset.png",
       plot = final_map, width = 14, height = 10, dpi = 400)

cat("\n✅ Pipeline map with zoomed-in inset saved to: Pipeline_Map_with_Inset.png\n")

# -----------------------------
# Route Summary Statistics
# -----------------------------
calculate_stats <- function(df, route_name) {
```

```
# Clean any NA coordinates
df <- df[complete.cases(df$Longitude, df$Latitude), ]

# Return early if not enough points
if (nrow(df) < 2) {
  cat(sprintf("\n⚠️ %s Route: Not enough valid points.\n", route_name))
  return(NULL)
}

# Get elevation
coords_sf <- st_as_sf(df, coords = c("Longitude", "Latitude"), crs = 4326)
elev_data <- elevatr::get_elev_point(coords_sf, src = "aws")
df$elevation <- elev_data$elevation

# Drop rows with NA elevation
df <- df[!is.na(df$elevation), ]
if (nrow(df) < 2) {
  cat(sprintf("\n⚠️ %s Route: Not enough valid elevation data.\n", route_name))
  return(NULL)
}

# Compute 3D distances
dists_2d <- distGeo(df[-nrow(df), c("Longitude", "Latitude")], df[-1, c("Longitude", "Latitude")])
dz <- diff(df$elevation)
dists_3d <- sqrt(dists_2d^2 + dz^2) / 1000  # in km
pipe_length <- sum(dists_3d)

# Elevation gain
elevation_gain <- sum(dz[dz > 0], na.rm = TRUE)

# Geometry cleanup
line_coords <- as.matrix(df[, c("Longitude", "Latitude")])
if (any(is.na(line_coords))) {
  cat(sprintf("\n⚠️ %s Route: NA in coordinates for LINESTRING creation.\n", route_name))
  return(NULL)
}

route_line <- tryCatch({
  st_linestring(line_coords, dim = "XY")  # force 2D
}, error = function(e) {
  cat(sprintf("\n❌ LINESTRING creation failed for %s: %s\n", route_name, e$message))
  return(NULL)
})

route_sf <- st_sf(geometry = st_sfc(route_line, crs = 4326))

# Intersections
intersects_pa <- sum(st_intersects(route_sf, protected_areas, sparse = FALSE))
intersects_faults <- sum(st_intersects(route_sf, fault_lines, sparse = FALSE))

# Final Output
cat(sprintf("\n📍 %s Route:\n- Pipe Length (3D): %.2f km\n- Elevation Gain: %.2f m\n- Protected Areas Crossed: %d\n-
Fault Lines Crossed: %d\n",
```

```
        route_name, pipe_length, elevation_gain, intersects_pa, intersects_faults))
}



# Run stats per route
calculate_stats(route1_df, "Direct Path")
calculate_stats(route2_df, "Leyte Waypoint")
calculate_stats(route3_df, "Camiguin Waypoint")


# -----------------------------
# Elevation Profile Plot using 3D Pipe Length
# -----------------------------
get_elevation_profile_3d <- function(df, label) {
  df <- df[complete.cases(df$Longitude, df$Latitude), ]
  if (nrow(df) < 2) return(NULL)

  coords_sf <- st_as_sf(df, coords = c("Longitude", "Latitude"), crs = 4326)
  elev_data <- elevatr::get_elev_point(coords_sf, src = "aws")
  df$elevation <- elev_data$elevation

  df <- df[!is.na(df$elevation), ]
  if (nrow(df) < 2) return(NULL)

  dists_2d <- distGeo(df[-nrow(df), c("Longitude", "Latitude")], df[-1, c("Longitude", "Latitude")])
  dz <- diff(df$elevation)
  dists_3d <- sqrt(dists_2d^2 + dz^2) / 1000  # km
  cum_dist <- c(0, cumsum(dists_3d))

  data.frame(
    Distance_3D_km = cum_dist,
    Elevation_m = df$elevation,
    Route = label
  )
}

# Compute profiles
elev1 <- get_elevation_profile_3d(route1_df, "Direct Path")
elev2 <- get_elevation_profile_3d(route2_df, "Leyte Waypoint")
elev3 <- get_elevation_profile_3d(route3_df, "Camiguin Waypoint")
profile_all <- bind_rows(elev1, elev2, elev3)

# Plot
elev_plot <- ggplot(profile_all, aes(x = Distance_3D_km, y = Elevation_m, color = Route)) +
  geom_line(size = 1) +
  facet_wrap(~Route, ncol = 1, scales = "free_x") +
  labs(
    title = "Elevation vs. 3D Pipe Length for Pipeline Routes",
    x = "Cumulative 3D Pipe Length (km)",
    y = "Elevation (m)"
  ) +
  scale_color_manual(values = c(
```

```
    "Direct Path" = "red",
    "Leyte Waypoint" = "blue",
    "Camiguin Waypoint" = "green"
  )) +
  theme_minimal()

# Save
ggsave("D:/USYD/Advanced Industrial Modelling/Project 1/Routing Maps/Elevation_Profile_3DStacked.png",
       plot = elev_plot, width = 10, height = 12, dpi = 400)

cat("\n✅ 3D Elevation profile plot saved to: Elevation_Profile_3DStacked.png\n")


# ----------------------------
# Export Camiguin Route Coordinates with Elevation and 3D Pipe Length
# ----------------------------
library(openxlsx)  # if not installed, run install.packages("openxlsx")

camiguin_profile <- get_elevation_profile_3d(route3_df, "Camiguin Waypoint")

# Add latitude (Y) from original df
camiguin_profile$Latitude <- route3_df$Latitude[seq_len(nrow(camiguin_profile))]

# Rename for clarity
camiguin_export <- camiguin_profile %>%
  select(x = Distance_3D_km, y = Latitude, z = Elevation_m)

# Save to Excel
write.xlsx(camiguin_export, "D:/USYD/Advanced Industrial Modelling/Project 1/Routing
Maps/Camiguin_ElevationProfile.xlsx", overwrite = TRUE)

cat("\n📄 Camiguin 3D coordinates saved to: Camiguin_ElevationProfile.xlsx\n")


library(geosphere)

# Compute 2D great-circle distances between consecutive points in the sea segment
seg2_distances <- distGeo(seg2_df[-nrow(seg2_df), ], seg2_df[-1, ])

# Convert to kilometers and sum
seabed_length_km <- sum(seg2_distances) / 1000

cat(sprintf("\n🌊 Projected Camiguin–Bohol seabed pipe length: %.2f km\n", seabed_length_km))
```

H. Hydraulic Modelling

```
# ----------------------------
# Load Required Libraries
# ----------------------------
library(dplyr)
library(ggplot2)
library(readxl)
```

```
library(openxlsx)
library(tidyr)

# -----------------------------
# Load Elevation Profile (Camiguin)
# -----------------------------
profile_path <- "D:/USYD/Advanced Industrial Modelling/Project 1/Maps/Camiguin_XYZ_Profile_Adjusted.xlsx"
elevation_df <- read_xlsx(profile_path)
colnames(elevation_df) <- c("Distance_km", "Elevation_m", "Longitude", "Latitude")

# Add proxy for bends
elevation_df <- elevation_df %>%
  mutate(Position_Y = seq(0, 1, length.out = nrow(elevation_df)))

# -----------------------------
# Pipeline and Fluid Properties
# -----------------------------
velocity_target <- 3.0          # m/s
pipe_diameter <- 1.0            # m
hw_coefficient <- 130           # Hazen-Williams C for HDPE
friction_factor <- 0.015        # Darcy friction
g <- 9.81                       # m/s²
pump_efficiency <- 0.75         # decimal
water_density <- 1000           # kg/m³

# -----------------------------
# Flow Scenarios (m³/s)
# -----------------------------
scenarios <- data.frame(
  Scenario = c("Baseline", "Moderate Dry Year", "Max Resilience"),
  FlowRate = c(0.793, 1.462, 2.023)
)

# -----------------------------
# Function to Calculate Head Losses
# -----------------------------
calculate_losses <- function(df, flow_rate, scenario_name) {
  velocity <- flow_rate / (pi * (pipe_diameter^2) / 4)

  df %>%
    mutate(
      Segment_Length_m = c(0, diff(Distance_km) * 1000),
      Bend_Diff = abs(c(0, diff(Position_Y))),
      K_minor = case_when(
        Bend_Diff < 0.1 ~ 0.1,
        Bend_Diff < 0.45 ~ 0.3,
        TRUE ~ 0.5
      ),
      Minor_HeadLoss = K_minor * (velocity^2 / (2 * g)),
      HeadLoss_Darcy = friction_factor * (Segment_Length_m / pipe_diameter) * (velocity^2 / (2 * g)),
      HeadLoss_HW = ifelse(
        Segment_Length_m == 0,
        0,
```

```
      10.67 * (Segment_Length_m / (hw_coefficient^1.852 * pipe_diameter^4.87)) * flow_rate^1.852
    ),
    Total_Darcy = HeadLoss_Darcy + Minor_HeadLoss,
    Total_HW = HeadLoss_HW + Minor_HeadLoss,
    Scenario = scenario_name
  )
}

# -----------------------------
# Apply to All Scenarios
# -----------------------------
loss_data <- bind_rows(
  calculate_losses(elevation_df, scenarios$FlowRate[1], scenarios$Scenario[1]),
  calculate_losses(elevation_df, scenarios$FlowRate[2], scenarios$Scenario[2]),
  calculate_losses(elevation_df, scenarios$FlowRate[3], scenarios$Scenario[3])
)

# -----------------------------
# Head Loss Summary
# -----------------------------
loss_summary <- loss_data %>%
  group_by(Scenario) %>%
  summarise(
    Minor = sum(Minor_HeadLoss, na.rm = TRUE),
    DW = sum(HeadLoss_Darcy, na.rm = TRUE),
    HW = sum(HeadLoss_HW, na.rm = TRUE)
  ) %>%
  mutate(
    Total_DW = DW + Minor,
    Total_HW = HW + Minor
  )

# -----------------------------
# Pumping Power Calculation
# -----------------------------
power_summary <- loss_summary %>%
  left_join(scenarios, by = "Scenario") %>%
  mutate(
    PumpPower_DW_kW = (water_density * g * FlowRate * Total_DW) / (pump_efficiency * 1000),
    PumpPower_HW_kW = (water_density * g * FlowRate * Total_HW) / (pump_efficiency * 1000)
  )

# -----------------------------
# Elevation and Pressure Head
# -----------------------------
elevation_head_dz <- 22  # Confirmed manually
pressure_head_dp <- 0    # Open-to-open system

# -----------------------------
# Pumping Head Summary Table
# -----------------------------
pumping_summary <- loss_summary %>%
  left_join(scenarios, by = "Scenario") %>%
```

```
  mutate(
    Elevation_Head_dz = elevation_head_dz,
    Pressure_Head_dp = pressure_head_dp,
    Estimated_Pumping_Head_DW = Total_DW + Elevation_Head_dz,
    Estimated_Pumping_Head_HW = Total_HW + Elevation_Head_dz
  ) %>%
  select(Scenario, Minor, DW, HW, Total_DW, Total_HW,
         Elevation_Head_dz, Pressure_Head_dp,
         Estimated_Pumping_Head_DW, Estimated_Pumping_Head_HW)

# -----------------------------
# Export All to Excel (3 Sheets)
# -----------------------------
wb <- createWorkbook()
addWorksheet(wb, "HeadLoss_Summary")
addWorksheet(wb, "Power_Summary")
addWorksheet(wb, "Pumping_Head_Summary")

writeData(wb, "HeadLoss_Summary", loss_summary)
writeData(wb, "Power_Summary", power_summary)
writeData(wb, "Pumping_Head_Summary", pumping_summary)

output_path <- "D:/USYD/Advanced Industrial Modelling/Project 1/Pump Models/Camiguin_HeadLoss_And_Power.xlsx"
saveWorkbook(wb, output_path, overwrite = TRUE)

cat("\n✅ Final Excel workbook saved to:\n", output_path, "\n")
```

G. Pressure Profiles

```
# -----------------------------
# Install & Load Required Libraries
# -----------------------------
packages_needed <- c("dplyr", "ggplot2", "readxl", "openxlsx", "scales")
new_packages <- packages_needed[!(packages_needed %in% installed.packages()[,"Package"])]
if(length(new_packages)) install.packages(new_packages)

library(dplyr)
library(ggplot2)
library(readxl)
library(openxlsx)
library(scales)

# -----------------------------
# Load Pipeline Data from Excel
# -----------------------------
file_path <- "D:/USYD/Advanced Industrial Modelling/Project 1/Routing Maps/Camiguin XYZ Coordinates.xlsx"
pipeline_data <- read_excel(file_path)
colnames(pipeline_data) <- c("x", "y", "z")  # x/y in km, z in meters

# -----------------------------
# Compute Geometry and Segment Distances
# -----------------------------
horizontal_dist <- c(0, sqrt(diff(pipeline_data$x)^2 + diff(pipeline_data$y)^2)) * 1000
```

```
elev_diff <- c(0, diff(pipeline_data$z))
segment_length <- sqrt(horizontal_dist^2 + elev_diff^2)
pipe_length <- cumsum(segment_length)

pipeline_data <- pipeline_data %>%
  mutate(
    segment_length = segment_length,
    pipe_length = pipe_length,
    z_m = z,
    Bend_Diff = c(0, abs(diff(z_m))),
    K_minor = case_when(
      Bend_Diff < 5 ~ 0.1,
      Bend_Diff < 20 ~ 0.3,
      TRUE ~ 0.5
    )
  )

# -----------------------------
# Hydraulic Parameters (Max Resilience)
# -----------------------------
flow_rate <- 2.023
pipe_diameter <- 1.0
friction_factor <- 0.015
g <- 9.81
rho <- 1000
initial_pressure <- 101325

pipe_area <- pi * (pipe_diameter / 2)^2
velocity <- flow_rate / pipe_area

# -----------------------------
# Compute Head Losses & Pressure Head
# -----------------------------
pipeline_data <- pipeline_data %>%
  mutate(
    HeadLoss_Darcy = friction_factor * (segment_length / pipe_diameter) * (velocity^2 / (2 * g)),
    HeadLoss_Minor = K_minor * (velocity^2 / (2 * g)),
    Total_HeadLoss_Segment = HeadLoss_Darcy + HeadLoss_Minor,
    Elevation_Change = z_m - first(z_m),
    Cumulative_HeadLoss = cumsum(Total_HeadLoss_Segment),
    Pressure_Bernoulli_Pa = initial_pressure - (rho * g * Elevation_Change) - (rho * g * Cumulative_HeadLoss),
    Pressure_Head_m = Pressure_Bernoulli_Pa / (rho * g)
  )

# -----------------------------
# Plot: Elevation, Pressure Head, Segment Head Loss
# -----------------------------
ggplot(pipeline_data, aes(x = pipe_length)) +
  geom_line(aes(y = z_m, color = "Elevation Head"), size = 1.2, linetype = "dashed") +
  geom_line(aes(y = Pressure_Head_m, color = "Pressure Head"), size = 1.2) +
  geom_line(aes(y = Total_HeadLoss_Segment, color = "Head Loss per Segment"), size = 1.2) +
  scale_color_manual(
    name = "Head Components",
```

```
    values = c(
      "Elevation Head" = "darkorange",
      "Pressure Head" = "royalblue",
      "Head Loss per Segment" = "darkgreen"
    )
  ) +
  labs(
    title = "Pipeline Profile: Elevation, Pressure Head, and Segment Head Loss",
    x = "Pipeline Length (m)",
    y = "Head (m)"
  ) +
  theme_minimal() +
  theme(
    legend.position = "top",
    axis.title.y = element_text(color = "black")
  )

# -----------------------------
# Export to Excel
# -----------------------------
output_df <- pipeline_data %>%
  select(pipe_length, segment_length, z_m, Total_HeadLoss_Segment, Pressure_Head_m)

write.xlsx(output_df,
           "D:/USYD/Advanced Industrial Modelling/Project 1/Pump Models/Camiguin_3HeadComponents_Final.xlsx")

cat("\n✅ Final 3-component head profile exported to Excel.\n")
```

I. Pumping Layouts

```
# -----------------------------
# Load Required Libraries
# -----------------------------
library(dplyr)
library(ggplot2)
library(readxl)
library(openxlsx)
library(scales)

# -----------------------------
# Load Pipeline Data
# -----------------------------
file_path <- "D:/USYD/Advanced Industrial Modelling/Project 1/Routing Maps/Camiguin XYZ Coordinates.xlsx"
pipeline_data <- read_excel(file_path)
colnames(pipeline_data) <- c("x", "y", "z")  # x/y in km, z in meters

# Compute distances and geometry
horizontal_dist <- c(0, sqrt(diff(pipeline_data$x)^2 + diff(pipeline_data$y)^2)) * 1000
segment_length <- sqrt(horizontal_dist^2 + c(0, diff(pipeline_data$z))^2)
pipe_length <- cumsum(segment_length)

pipeline_data <- pipeline_data %>%
```

```
  mutate(pipe_length = pipe_length, z_m = z)

# -----------------------------
# Final Pump Models and Scenarios
# -----------------------------
pumps <- data.frame(
  Model = c("KSB Omega 300-700", "Grundfos CRN 185-6", "Flowserve DMX"),
  Max_Flow_m3h = c(2000, 251.9, 5000),
  Max_Head_m = c(200, 253.8, 600),
  stringsAsFactors = FALSE
)
pumps$Max_Flow_m3s <- pumps$Max_Flow_m3h / 3600

scenarios <- data.frame(
  Scenario = factor(c("Baseline", "Moderate Dry Year", "Maximum Resilience"),
                    levels = c("Baseline", "Moderate Dry Year", "Maximum Resilience")),
  FlowRate = c(0.793, 1.462, 2.023),
  HeadRequired = c(233.45, 686.12, 1293.58)
)

pipe_length_km <- max(pipeline_data$pipe_length) / 1000

# -----------------------------
# Optimization Function (Adjusted to prioritize upstream & avoid underwater)
# -----------------------------
optimize_layout <- function(flow, head, pump_flow, pump_head, pipeline_df) {
  n_parallel <- ceiling(flow / pump_flow)
  n_series <- max(1, ceiling(head / pump_head))
  spacing_m <- max(pipeline_df$pipe_length) / n_series

  # Prioritize placing pumps upstream first
  station_positions <- (seq_len(n_series) - 1) * spacing_m

  # Avoid underwater pumps (e.g., only place if elevation >= 0)
  elevations <- approx(pipeline_df$pipe_length, pipeline_df$z_m, xout = station_positions)$y
  station_positions <- station_positions[elevations >= 0]

  return(data.frame(
    Station_ID = paste0("P", seq_along(station_positions)),
    pipe_length = station_positions,
    n_parallel = rep(n_parallel, length(station_positions))
  ))
}

# -----------------------------
# Simulate All Layouts (All Pumps × Scenarios)
# -----------------------------
layout_all <- list()

for (i in 1:nrow(scenarios)) {
  for (j in 1:nrow(pumps)) {
    scen <- scenarios[i, ]
    pump <- pumps[j, ]
```

```
    layout_df <- optimize_layout(
      flow = scen$FlowRate,
      head = scen$HeadRequired,
      pump_flow = pump$Max_Flow_m3s,
      pump_head = pump$Max_Head_m,
      pipeline_df = pipeline_data
    )

    layout_df$Scenario <- scen$Scenario
    layout_df$Pump_Model <- pump$Model

    # Add elevation and XY coordinates
    layout_df$Elevation <- approx(pipeline_data$pipe_length, pipeline_data$z_m, xout = layout_df$pipe_length)$y
    layout_df$Longitude <- approx(pipeline_data$pipe_length, pipeline_data$x, xout = layout_df$pipe_length)$y
    layout_df$Latitude <- approx(pipeline_data$pipe_length, pipeline_data$y, xout = layout_df$pipe_length)$y

    layout_all[[paste(scen$Scenario, pump$Model)]] <- layout_df
  }
}

pump_stations_all <- bind_rows(layout_all)

# -----------------------------
# Plot 9 Pump Layouts
# -----------------------------
pump_stations_all$Facet_Col <- pump_stations_all$Pump_Model
pump_stations_all$Scenario <- factor(pump_stations_all$Scenario,
                                     levels = c("Baseline", "Moderate Dry Year", "Maximum Resilience"))

# Plot
ggplot() +
  geom_line(data = pipeline_data, aes(x = pipe_length / 1000, y = z_m), size = 0.8, color = "black") +
  geom_point(data = pump_stations_all, aes(x = pipe_length / 1000, y = Elevation, fill = Scenario),
             shape = 21, size = 4, color = "black") +
  geom_text(data = pump_stations_all,
            aes(x = pipe_length / 1000, y = Elevation + 200,
                label = paste0("x", n_parallel)),
            size = 5, fontface = "bold") +
  facet_grid(rows = vars(Scenario), cols = vars(Facet_Col)) +
  scale_fill_manual(values = c("Baseline" = "brown", "Moderate Dry Year" = "blue", "Maximum Resilience" =
"forestgreen")) +
  labs(
    title = "Elevation Profile with Upstream-Optimized Pump Stations (9 Layouts)",
    x = "Pipeline Length (km)",
    y = "Elevation (m)",
    fill = "Scenario"
  ) +
  theme_minimal() +
  theme(
    legend.position = "top",
    strip.text = element_text(size = 20, face = "bold"),
    axis.title = element_text(size = 18),        # Axis label size
```

```
    axis.text = element_text(size = 14)          # Axis number (tick label) size
  )


# -----------------------------
# Export to Excel
# -----------------------------
write.xlsx(pump_stations_all, "D:/USYD/Advanced Industrial Modelling/Project 1/Pump
Models/AllScenarios_FinalPumpLayouts_UpstreamOnly.xlsx")

cat("\n✅ Pump layout optimized to start upstream and avoid submerged stations. Saved to Excel.\n")
```

J. Pump Costs

```
# -----------------------------
# Load Libraries
# -----------------------------
library(dplyr)
library(ggplot2)
library(tidyr)
library(scales)

# -----------------------------
# Assumptions from Section 4.2
# -----------------------------
rho <- 1000
g <- 9.81
Q <- 0.793
H <- 233.45
eta <- 0.75
hours_per_day <- 24
php_per_kwh <- 9.00
annual_increase <- 0.04
discount_rate <- 0.08
markup_OM <- 0.10
years <- 20
usd_conversion <- 55

# -----------------------------
# Energy Requirement Calculation
# -----------------------------
power_kw <- (rho * g * Q * H) / (eta * 1000)
daily_energy_kwh <- power_kw * hours_per_day

opex_npv <- 0
for (t in 1:years) {
  rate_t <- php_per_kwh * (1 + annual_increase)^(t - 1)
  annual_cost <- daily_energy_kwh * 365 * rate_t
  opex_npv <- opex_npv + (annual_cost / (1 + discount_rate)^t)
}
opex_npv_total <- opex_npv * (1 + markup_OM)

# -----------------------------
```

```
# Revenue NPV Calculation
# -----------------------------
daily_volume <- Q * 86400
tariff_base <- 35
tariff_escalation <- 0.03
revenue_npv <- 0
for (t in 1:years) {
  tariff_t <- tariff_base * (1 + tariff_escalation)^(t - 1)
  annual_revenue <- daily_volume * tariff_t * 365
  revenue_npv <- revenue_npv + (annual_revenue / (1 + discount_rate)^t)
}

# -----------------------------
# Define Pump Models and Base Costs
# -----------------------------
pump_capex <- data.frame(
  Pump_Model = c("Flowserve DMX", "KSB Omega 300-700", "Grundfos CRN 185-6"),
  Pump_Only_CAPEX = c(6 * 6420000, 28 * 2140000, 174 * 4280000)
)

# -----------------------------
# Infrastructure CAPEX Multipliers
# -----------------------------
infra_multipliers <- list(
  Pipeline = 15.0,
  Civil_Works = 1.5,
  Land = 0.5,
  Electrical_SCADA = 0.5,
  Environment = 0.125,
  Contingency = 2.0
)

pump_capex <- pump_capex %>%
  rowwise() %>%
  mutate(
    Pipeline = Pump_Only_CAPEX * infra_multipliers$Pipeline,
    Civil_Works = Pump_Only_CAPEX * infra_multipliers$Civil_Works,
    Land = Pump_Only_CAPEX * infra_multipliers$Land,
    Electrical_SCADA = Pump_Only_CAPEX * infra_multipliers$Electrical_SCADA,
    Environment = Pump_Only_CAPEX * infra_multipliers$Environment,
    Contingency = Pump_Only_CAPEX * infra_multipliers$Contingency
  ) %>%
  ungroup()

# -----------------------------
# Discount CAPEX to NPV
# -----------------------------
pump_capex_discounted <- pump_capex %>%
  mutate(across(c(Pump_Only_CAPEX, Pipeline, Civil_Works, Land, Electrical_SCADA, Environment, Contingency),
                ~ .x / (1 + discount_rate))) %>%
  mutate(
    Infra_Total = Pipeline + Civil_Works + Land + Electrical_SCADA + Environment + Contingency,
    Total_CAPEX = Pump_Only_CAPEX + Infra_Total
```

```
  )

# -----------------------------
# Combine Costs and Calculate Metrics
# -----------------------------
comparison_npv <- pump_capex_discounted %>%
  mutate(
    NPV_OPEX = round(opex_npv_total, 0),
    NPV_Revenue = round(revenue_npv, 0),
    Total_NPV_Cost = Total_CAPEX + opex_npv_total,
    Net_Present_Value = NPV_Revenue - Total_NPV_Cost,
    BCR = round(NPV_Revenue / Total_NPV_Cost, 2)
  ) %>%
  mutate(across(where(is.numeric), ~ round(.x)))

# -----------------------------
# Prepare Breakdown for Plot
# -----------------------------
capex_npv_breakdown <- pump_capex_discounted %>%
  select(Pump_Model, Pump_Only_CAPEX, Pipeline, Civil_Works, Land, Electrical_SCADA, Environment, Contingency)
%>%
  rename(Pump = Pump_Only_CAPEX) %>%
  pivot_longer(cols = -Pump_Model, names_to = "Component", values_to = "Cost_Type_Value")

# Use correct total OPEX and split into energy + O&M markup
energy_share <- opex_npv / opex_npv_total

opex_npv_breakdown <- pump_capex_discounted %>%
  select(Pump_Model) %>%
  mutate(
    Energy_Cost = opex_npv_total * energy_share,
    OM_Markup = opex_npv_total * (1 - energy_share)
  ) %>%
  pivot_longer(cols = -Pump_Model, names_to = "Component", values_to = "Cost_Type_Value")

cost_breakdown_combined_npv <- bind_rows(capex_npv_breakdown, opex_npv_breakdown)

# -----------------------------
# Plot Final Stacked Bar with Cost and Revenue Labels
# -----------------------------
ggplot(cost_breakdown_combined_npv, aes(x = Pump_Model, y = Cost_Type_Value / 1e9, fill = Component)) +
  geom_bar(stat = "identity", position = "stack") +
  geom_point(data = comparison_npv, aes(x = Pump_Model, y = NPV_Revenue / 1e9),
             color = "black", shape = 18, size = 4, inherit.aes = FALSE) +

  # Total Cost Labels
  geom_text(data = comparison_npv,
            aes(x = Pump_Model,
                y = (Total_NPV_Cost / 1e9) + 0.3,
                label = paste0("₱", round(Total_NPV_Cost / 1e9, 2), "B\n($", round(Total_NPV_Cost / 1e6 / usd_conversion),
"M)")),
            size = 8, fontface = "bold", inherit.aes = FALSE) +
```

```
  # Revenue Labels
  geom_text(data = comparison_npv,
          aes(x = Pump_Model,
              y = (NPV_Revenue / 1e9) + 0.2,
              label = paste0("Revenue ₱", round(NPV_Revenue / 1e9, 2), "B\n($", round(NPV_Revenue / 1e6 / usd_conversion),
"M)")),
          size = 8, fontface = "italic", color = "black", inherit.aes = FALSE) +

  labs(
    title = "NPV-Based Lifecycle Cost Breakdown with Revenue by Pump Model",
    x = "Pump Model",
    y = "₱ Billion (Discounted)",
    fill = "Cost Component"
  ) +
  scale_y_continuous(labels = label_number(suffix = "B")) +
  theme_minimal() +
  theme(
    legend.position = "right",
    plot.title = element_text(size = 14, face = "bold", hjust = 0.5),
    axis.title.x = element_text(size = 24, face = "bold"),
    axis.title.y = element_text(size = 24, face = "bold"),
    axis.text.x = element_text(size = 22),
    axis.text.y = element_text(size = 22),
    legend.title = element_text(size = 22, face = "bold"),
    legend.text = element_text(size = 22)
  )

# -----------------------------
# Final Summary Table Output
# -----------------------------
summary_table <- comparison_npv %>%
  select(Pump_Model, Total_CAPEX, NPV_OPEX, Total_NPV_Cost, NPV_Revenue, Net_Present_Value, BCR) %>%
  mutate(
    Total_CAPEX_B = round(Total_CAPEX / 1e9, 2),
    NPV_OPEX_B = round(NPV_OPEX / 1e9, 2),
    Total_NPV_Cost_B = round(Total_NPV_Cost / 1e9, 2),
    NPV_Revenue_B = round(NPV_Revenue / 1e9, 2),
    Net_Present_Value_B = round(Net_Present_Value / 1e9, 2),
    Total_NPV_Cost_USD = round(Total_NPV_Cost / usd_conversion / 1e6),
    NPV_Revenue_USD = round(NPV_Revenue / usd_conversion / 1e6)
  ) %>%
  select(
    Pump_Model,
    Total_CAPEX_B,
    NPV_OPEX_B,
    Total_NPV_Cost_B,
    Total_NPV_Cost_USD,
    NPV_Revenue_B,
    NPV_Revenue_USD,
    Net_Present_Value_B,
    BCR
  ) %>%
  rename(
```

```
    `Pump Model` = Pump_Model,
    `CAPEX (₱B)` = Total_CAPEX_B,
    `OPEX (₱B)` = NPV_OPEX_B,
    `Total NPV Cost (₱B)` = Total_NPV_Cost_B,
    `Total NPV Cost (USD M)` = Total_NPV_Cost_USD,
    `NPV Revenue (₱B)` = NPV_Revenue_B,
    `NPV Revenue (USD M)` = NPV_Revenue_USD,
    `Net Present Value (₱B)` = Net_Present_Value_B,
    `Benefit-Cost Ratio` = BCR
  )

print(summary_table)
```

K. Project Impacts

```
# --- Inter-Basin Transfer Impact Model (R Script) ---

# --- PARAMETERS ---
# General
annual_transfer_mcm <- 63.8
population_cebu <- 3000000

domestic_demand_lpcd <- 150
industrial_demand_lpcd <- 50
total_demand_lpcd <- domestic_demand_lpcd + industrial_demand_lpcd

# Economic & Labor
capex_usd <- 51071429
opex_usd <- 1.77e7
jobs_per_million_capex <- 12.5
jobs_per_million_opex <- 8

historic_drought_losses <- 15e6  # USD
coverage_rate <- 0.9

area_farmland_ha <- 1000
yield_gain_ton_per_ha <- 1.2
price_per_ton <- 250  # USD

# Energy & Emissions
energy_kwh_per_year <- 21211.87
emission_factor <- 0.0.024  # kg CO2 per kWh for hydro, 0.7 for oil and coal

# Marine Impact
seabed_area_disturbed_km2 <- 0.1  # Assumed
biodiversity_impact_index <- 0.3  # 0 = low, 1 = high (placeholder)

# --- SOCIAL IMPACTS ---
# LPCD Gain
annual_transfer_liters <- annual_transfer_mcm * 1e6 * 1000
increase_lpcd <- annual_transfer_liters / (population_cebu * 365)

# Job Creation
```

```
jobs_construction <- (capex_usd / 1e6) * jobs_per_million_capex
jobs_operations <- (opex_usd / 1e6) * jobs_per_million_opex

# --- ECONOMIC IMPACTS ---
# --- DROUGHT LOSS AVOIDANCE BASED ON DEFICIT RESOLUTION AND GLOBAL DATA ---
max_deficit_mcm <- 57.2  # Based on 2050, 1-in-10 dry year
loss_per_mcm <- 10000    # Estimated from global literature scaled to PH context
historic_drought_losses <- max_deficit_mcm * loss_per_mcm  # = $572,000

# Proportion of deficit resolved
deficit_covered_fraction <- min(annual_transfer_mcm / max_deficit_mcm, 1.0)
avoided_drought_losses <- historic_drought_losses * deficit_covered_fraction * coverage_rate
# Agricultural Gains
additional_agri_revenue <- area_farmland_ha * yield_gain_ton_per_ha * price_per_ton

# --- ENVIRONMENTAL IMPACTS ---
# Carbon Emissions
annual_co2_tons <- (energy_kwh_per_year * emission_factor) / 1000

# Marine Biodiversity Impact (simplified index-based)
marine_impact_score <- seabed_area_disturbed_km2 * biodiversity_impact_index

# --- RESULTS SUMMARY ---
impact_summary <- data.frame(
  Category = c(
    "Water Availability Increase (LPCD)",
    "Jobs Created (Construction Phase)",
    "Jobs Created (Operations Phase)",
    "Avoided Economic Losses from Drought (USD)",
    "Increased Agricultural Revenue (USD)",
    "Annual CO2 Emissions (tons)",
    "Marine Biodiversity Impact Score"
  ),
  Estimate = round(c(
    increase_lpcd,
    jobs_construction,
    jobs_operations,
    avoided_drought_losses,
    additional_agri_revenue,
    annual_co2_tons,
    marine_impact_score
  ), 2)
)

print(impact_summary)
```

L. Economic Impact with Risk Mitigation

```
# -----------------------------
# Load Libraries
# -----------------------------
library(dplyr)
library(tibble)
```

```
library(ggplot2)
library(scales)
library(tidyr)

# -----------------------------
# Flowserve DMX Cost Inputs
# -----------------------------
conversion_rate <- 56  # PHP to USD

# Base cost components in PHP
capex_php <- 2.86e9     # Flowserve DMX CAPEX
opex_php <- 0.99e9      # Flowserve DMX NPV OPEX
base_cost_php <- capex_php + opex_php  # ₱3.85B total

# Risk mitigation percentages based on literature
risk_pct <- c(0, 0.28, 0.36, 0.40)  # 0%, 28%, 36%, 40%

# Revenue NPV (₱)
revenue_npv_php <- 10.72e9

# -----------------------------
# Summary Table with PHP and USD
# -----------------------------
scenarios <- c("Base Only", "Base + Min", "Base + Avg", "Base + Max")
risk_costs_php <- base_cost_php * risk_pct

summary_df <- tibble(
  Scenario = scenarios,
  CAPEX_PHP = capex_php,
  OPEX_PHP = opex_php,
  Risk_PHP = risk_costs_php,
  Total_PHP = capex_php + opex_php + risk_costs_php,
  Revenue_PHP = revenue_npv_php
) %>%
  mutate(
    Profit_PHP = Revenue_PHP - Total_PHP,
    CAPEX_USD = CAPEX_PHP / conversion_rate,
    OPEX_USD = OPEX_PHP / conversion_rate,
    Risk_USD = Risk_PHP / conversion_rate,
    Total_USD = Total_PHP / conversion_rate,
    Revenue_USD = Revenue_PHP / conversion_rate,
    Profit_USD = Profit_PHP / conversion_rate
  )

print(summary_df)

# -----------------------------
# Prepare Stacked Bar Plot Data (in USD)
# -----------------------------
stacked_data_usd <- summary_df %>%
  select(Scenario, CAPEX_USD, OPEX_USD, Risk_USD) %>%
  rename(CAPEX = CAPEX_USD, OPEX = OPEX_USD, `Risk Mitigation` = Risk_USD) %>%
  pivot_longer(cols = c("CAPEX", "OPEX", "Risk Mitigation"),
```

```
              names_to = "Component", values_to = "Cost")

# Labels for revenue and profit
plot_labels_usd <- summary_df %>%
  select(Scenario, Revenue_USD, Profit_USD, Total_USD)

# -----------------------------
# Plot (in USD) with Increased Font Sizes
# -----------------------------
ggplot(stacked_data_usd, aes(x = Scenario, y = Cost / 1e6, fill = Component)) +
  geom_bar(stat = "identity", width = 0.5) +

  # Revenue point
  geom_point(data = plot_labels_usd, aes(x = Scenario, y = Revenue_USD / 1e6),
             shape = 18, size = 4, color = "black", inherit.aes = FALSE) +

  # Profit labels
  geom_text(data = plot_labels_usd,
            aes(x = Scenario, y = Revenue_USD / 1e6 + 10,
                label = paste0("Profit: $", round(Profit_USD / 1e6, 2), "M")),
            size = 7.5, fontface = "bold", color = "forestgreen", inherit.aes = FALSE) +

  # Total cost labels
  geom_text(data = plot_labels_usd,
            aes(x = Scenario, y = Total_USD / 1e6 + 25,
                label = paste0("Total: $", round(Total_USD / 1e6, 2), "M")),
            size = 7.5, fontface = "plain", inherit.aes = FALSE) +

  labs(
    title = "Flowserve DMX: Lifecycle Cost Breakdown (USD)",
    subtitle = "Includes CAPEX, OPEX, and Risk Mitigation with NPV Revenue",
    x = NULL,
    y = "Cost (USD $ Millions)",
    fill = "Component"
  ) +
  scale_y_continuous(labels = label_number(suffix = "M"), expand = expansion(mult = c(0, 0.15))) +
  scale_fill_manual(values = c("CAPEX" = "#9ecae1", "OPEX" = "#fdd0a2", "Risk Mitigation" = "#fc9272")) +
  theme_minimal(base_size = 16) +
  theme(
    legend.position = "top",
    legend.title = element_text(size = 20),
    legend.text = element_text(size = 20),
    axis.text.x = element_text(angle = 0, size = 15),
    axis.text.y = element_text(size = 20),
    axis.title.y = element_text(size = 20),
    plot.title = element_text(hjust = 0.5, face = "bold", size = 18),
    plot.subtitle = element_text(hjust = 0.5, size = 16)
  )
```

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Pipeline water transportation project: from Amazon basin to Atacama desert

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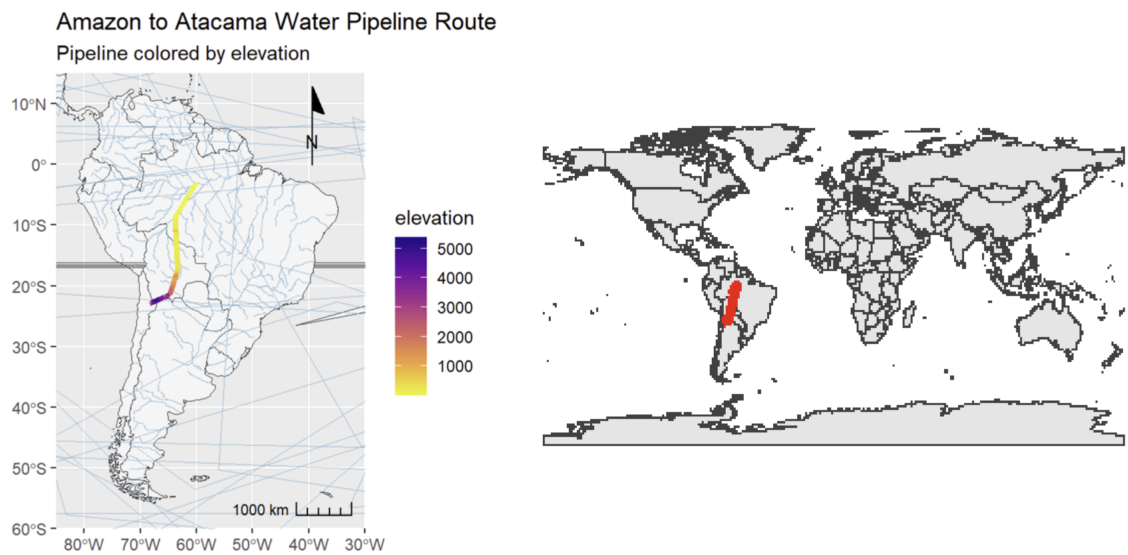
Graphical Abstract



Abstract

This study proposes a transcontinental water transfer system addressing Atacama Desert scarcity through Amazon Basin surplus redistribution. The infrastructure employs multistage pumping stations (4,000–6,000 m elevation gradients) with PLC-controlled pressure regulation, achieving 92% energy efficiency via adaptive modulation and turbine recovery. A hybrid financing model (public-private partnerships, metered tariffs) supports US$1.55 billion CAPEX and US$148.5 million annual OPEX, ensuring 20-year ROI. Closed-loop infrastructure maintains <1% leakage, minimizing ecological impacts while meeting regional daily demand (125,000 tons, 5,200 tons/hour). The system aligns with SDGs 6 and 13, demonstrating high replicability (UNEP index:0.87) through hydraulic resilience optimization and sustainable financing mechanisms for arid high-altitude regions.

1. Introduction

1.1 Problem Statement & Engineering Challenge

Atacama Desert lies in the west of the Andes in South America. It is famous as the driest desert in the world, and in some areas, there is virtually no annual rainfall. Because of the Andes, rain clouds from the east of the mountain range cannot come over, and because the Peru Current, which is one of the world's leading upwelling areas and a cold current, flows on the sea side, low pressure zones necessary for rain cloud formation do not form, making it very dry.

As the largest tropical rainforest in the world, the Amazon Basin is part of the Amazon River and is located in South America. The Amazon Basin covers an area of approximately 7,000,000 km2 (2,700,000 sq mile) [1], which is about 35.5% of the South American continent. The aim of the project is transferring abundant water resources from the Amazon basin to Atacama desert and its surroundings to release water stress of South America.

1.2 Background Research

The required water demand was estimated based on population and industrial needs in the Atacama Desert region. With a total population of approximately 650,000, considering an average per capita water consumption of 100 liters per day, the domestic water demand was estimated to be approximately 60,000 tons per day, industrial and agricultural included. Consequently, the total daily water requirement for the region was determined to be approximately 125,000 tons, equating to an hourly demand of around 5,200 tons. The pipeline design also takes into account the possible flow growth caused by local population growth.

Main City	Population (2023)
Antofagasta	400,000
Calama	150,000
Other Small Town	100,000
Total	650,000

Table 1. Population of Atacama desert region [1].

Large-scale water transfer projects have been implemented around the world to address chronic water shortages in arid and semi-arid regions, providing valuable precedents for the Amazon to Atacama pipeline. Most notably, China's South-to-North Water Diversion Project, with a total water transfer line of more than 4,000 kilometers, transfers water resources from the Yangtze River and its tributaries in southern China to northern China where water resources are more scarce. Similarly, projects such as the Great Rivers Project in Libya transfer fossil groundwater from deep aquifers in the Sahara Desert to coastal cities, and the Lesotho Highlands Water Project supplies water to South Africa's industrial heartland. There are countless cases for transferring water from abundant water resources to more arid regions around the world, which contributes to the idea and foundation of this project. However, noteworthy points such as huge altitude gap, multinational routine and local ethical-cultural factors need to be addressed.

1.3 Project Scope & Innovation

The Amazon-to-Atacama pipeline project's scale and complexity demand innovative funding strategies that blend public and private capital. One option is government-supported financing through multilateral institutions like the World Bank or CAF, which prioritize long-term climate resilience and regional development. Public-Private Partnerships (PPPs) offer another route by sharing investment risks with private actors who manage and finance construction in exchange for long-term returns—an approach proven effective in Chile's infrastructure projects. A third method, user-pay systems, relies on metered water pricing for municipalities and industries, ensuring cost recovery and promoting water efficiency.

This study investigates the feasibility and optimal routine for transporting water to the Atacama Desert, a region with acute water scarcity. Water demand in the Atacama and surrounding areas was estimated, leading to an analysis of suitable pipeline dimensions and pump specifications for long-distance conveyance. The project's key challenges include significant altitude variations across mountainous terrain, funding complexities, and local socio-economic concerns. Technological innovations such as cascade pressurized pump systems, PLC-controlled energy stations, and modular pipeline construction reduce engineering difficulty and enhance long-term viability. Supporting infrastructure includes transfer pumps, water storage tanks, filtration units for Amazon Basin water, and insulated piping to manage extreme temperatures. The integration of advanced automation, smart pressure control, and scalable system design positions the project as a model for sustainable, high-altitude water redistribution infrastructure.

2. Method

2.1 Hydraulic modeling

R-script performs hydraulic modeling to analyze the flow characteristics of water through a long-distance pipeline. It calculates fluid velocity, pressure drop, and head loss using fundamental fluid dynamics and hydraulic equations. Below are the key methods used:

For calculating the fluid flow, the continuity equation for flow velocity is used below. The script calculates fluid velocity using the Continuity Equation.

$$v = \frac{Q}{A}$$

Q : Flow rate (m3/h) A : Pipe cross-sectional area (m^2)

To calculate the required pressure of the fluid, we used the Darcy–Weisbach equation. In fluid dynamics, the Darcy–Weisbach equation is an empirical equation that relates the head loss, or pressure loss, due to friction along a given length of pipe to the average velocity of the fluid flow for an incompressible fluid [2].

$$\Delta H = f \cdot \frac{LV^2}{2gD}$$

Where :

dH : Head Loss, f : Darcy friction factor,
L : Length of pipe, D : Diameter of pipe,
V : Velocity of the fluid, g : Gravity acceleration

For calculating elevation head loss, Bernoulli's Equation is used. The script estimates the potential energy loss due to elevation using.

$$h_{\text{loss}} = h_{\text{elevation}} \times \rho \times g$$

Where:
H elevation : Height difference (m)
ρ : Water density (kg/m^3) /
g : Gravitational acceleration (9.81 m/s^2)

The wall thickness design follows the modified Barlow's formula for thermoplastic pipes:

$$t = \frac{P \cdot D}{2S \cdot E \cdot F} + A$$

Where:

P = 8.3 MPa (Max operating pressure in Andean zones)
D = 914 mm (36" nominal diameter)
S = 34.5 MPa (HDPE long-term hydrostatic strength)
E = 0.87 (Joint efficiency)
F = 2.0 (Safety factor per ASME B31.4)
A = 5 mm (Abrasion/UV allowance)

2.2 Geospatial Analysis

Geospatial Analysis is used to plan and visualize a water pipeline route from the Amazon Basin to the Atacama Desert, integrating GIS data, elevation analysis, and visualization. A Universal Transverse Mercator (UTM) projection (utm_proj) for accurate distance calculations is defined by R-Programming. Geographic data is transformed between EPSG:4326 (WGS84, lat/lon) and UTM for different stages of processing.

For defining the pipeline route key waypoints (Amazon, intermediate locations, and Atacama) are used. The waypoints are connected as a linestring object in sf (Simple Features). And the route is densified (st_segmentize) to ensure a sampling resolution of 1 point per kilometer.

For loading GIS Data, natural Earth data (rnaturalearth) for world borders and rivers is used. The GIS data is transformed into the same projection (utm_proj) as the pipeline for spatial consistency. The rivers dataset is handled with error-catching (tryCatch) to avoid failures if the data is unavailable.

The elevation profile along the pipeline is generated. Sampling points are extracted from the pipeline line (st_line_sample). The sampled points are transformed back to EPSG:4326 to fetch elevation data. Elevation data is retrieved from AWS (Amazon Web Services) via (get_elev_point). Outliers are removed (elevations outside -500m to 9000m). The distance from the starting point is computed (st_distance).

Finally, Visualization is performed with ggplot2. Countries and rivers are plotted as background layers. The pipeline route is color-coded by elevation using viridis (plasma color scale). Map annotations: North arrow (annotation_north_arrow), Scale bar (annotation_scale), Custom coordinate limits to focus on South America. For Elevation Profile Chart: Distance vs. Elevation plot is created. A smooth line and area fill are used for visualization. High-altitude points (>4000m) are marked for visibility. Viridis color scale is used for elevation-based styling.

2.3 Optimization Techniques

Optimization techniques were employed to achieve cost-effectiveness, energy efficiency, and ecological sustainability in pipeline route selection and operational management. Firstly, hydraulic optimization was performed using a multi-objective genetic algorithm (Vector Evaluated Genetic Algorithm, VEGA), targeting the reduction of energy consumption by optimally scheduling pump operations. The model assessed various hydraulic scenarios considering hydrological variability, generating operational rules as piecewise functions to maximize efficiency under different water demand conditions [3]. Secondly, geospatial optimization leverages geographic information system (GIS) data to refine pipeline route selection. This method integrated elevation profiles and spatial constraints to identify routes minimizing elevation head loss and environmental impact. Route options were assessed using a combination of hydraulic modeling (Darcy–Weisbach and Bernoulli equations) and spatial analytics, thereby balancing infrastructure costs with operational expenses. Lastly, ecological flow value (EFV) optimization was conducted through a hydrodynamic-habitat coupled model using MIKE 21 FM-HD and PHASIM to maintain suitable ecological flow (SEF) thresholds. This holistic approach simultaneously satisfied habitat preservation, sediment transport, and water purification demands, ensuring the sustainability and ecological compatibility of the water transfer operation [4].

3. Results and Discussion

3.1 Internal Operating Conditions

3.1.1 Hydraulic Pressure

Referring to Section 1.2, the required flow rate was calculated to be 5,200 m3 per hour considering population. In addition, using the Pressure Drop calculation formula in Section 2.1, it is necessary to calculate the pressure loss due to friction in the pipe and the pressure loss according to the elevation change between two areas. The table 2 below shows the Pressure friction loss by pipe size.

Temperature : 20degC Water, Flow Rate : 5,200m3/h
Weight Density : 998.2kg/m3,Viscosity : 1001.6 kg/m s

Pipe Size (inch)	Velocity (m/s)	Renolds No.	Pressure Loss/100km (bar)
36	2.2	2,004,455	34.2
40	1.8	1,804,009	20.0
44	1.5	1,640,008	12.4
48	1.2	1,503,341	8.0
60	0.8	1,202,673	2.6

Table 2. Comparison of flow rate and pressure loss by pipe size.

Also, the pressure drop according to the elevation change was calculated according to Section 2.1, a pressure loss of about 9.98 kg/cm2 g occurs per 100 m. Assuming that the altitude of the Atacama Desert is about 4,000 m, a pressure of 399.4kg/cm2 is required.

$$P_{head}\ per\ 100\ m = 100m \times 998.2kg/m^3 \times 9.81m/s^2$$

$$= 978,236pa \approx 9.98kg/cm^2$$

$$P_{head} = 4,000m \times 998.2kg/m^3 \times 9.81m/s^2$$

$$= 39,169,368Pa = 399.4kg/cm^2$$

3.1.2 Temperature Profile

In terms of temperature, the Amazon area has a tropical rainforest climate with temperatures ranging from about 25 to 30 degrees. The Atacama Desert can reach over 30 degrees during the day, with an extreme temperature difference of 0 degree at night. Also, since the transport route passes through the high-altitude Andes Mountains, sub-zero temperatures are possible. In some high-altitude areas, it is necessary to apply heat-conserving insulation to the pipes.

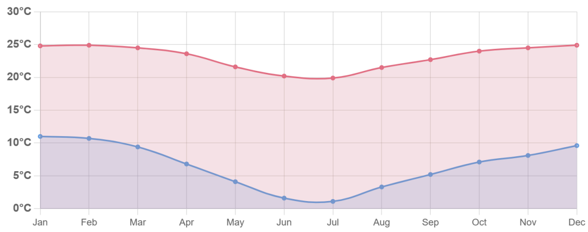


Figure 1. Atacama Desert Weather & Climate [5]

3.2 Water Quality Considerations

The quality of water in the Amazon varies depending on the rainy season and dry season, but usually shows a pH of 5.6 to 7.2 and a turbidity of 18 to 47.

Season/tide	Variables	Unit		
			Max	Min
Rainy ebbing tide	Temperature	°C	29	27
	pH	–	7.2	6.1
	DO	mg·L− 1	6.8	1.4
	BOD	mg·L− 1	18	6
	Thermotolerants coliforms	ThCU 100 mL− 1	2.42E + 05	1.48E + 03
	Total nitrogen	mg·L− 1	3.5	0.4
	Total phosphorus	mg·L− 1	0.5	0.05
	Total residue	mg·L− 1	53	26
	Turbidity	FTU	47	18
	WQI	–	60	29
Dry ebbing tide	Temperature	°C	30	27
	pH	–	6.6	5.6
	DO	mg·L− 1	7.5	5.3
	BOD	mg·L− 1	14	6
	Thermotolerants coliforms	ThCU 100 mL− 1	1.73E + 05	4.10E + 02
	Total nitrogen	mg·L− 1	1.1	0.2
	Total phosphorus	mg·L− 1	0.07	0.01
	Total residue	mg·L− 1	57	26
	Turbidity	FTU	34	22
	WQI	–	66	39

Table 3. Water Quality of Amazon River (adapted from *Adaelson Campelo Medeiros, et al.* 2017[6])

3.2.1 Total Dissolved Solids (TDS)

The implications of Total Dissolved Solids (TDS) are significant when considering the transport of water from the Amazon basin to the Atacama Desert. TDS levels in the Amazon River average 23.9 ± 17.8 mg/L, reflecting relatively solute-rich conditions compared to neighboring rivers, such as the Negro River, which is notably solute-poor (7.1 ± 6.7 mg/L) [7]. Elevated TDS levels increase the potential for scaling within pipelines, negatively impacting water transport efficiency, pipeline maintenance requirements, and soil-water interactions in the receiving environment. Thus, precise modeling of TDS along pipeline routes is essential for risk mitigation and maintenance planning.

3.2.2 Corrosive Elements

Corrosive elements, notably chloride and pH variations, substantially impact pipeline durability and operational reliability. The Amazon River exhibits circumneutral pH (6.6 ± 0.2), while the Negro River is more acidic (4.5±0.9), reflecting significant variability in regional water chemistry [7]. Such variability can enhance corrosion, biofouling, and scaling, necessitating regular monitoring and adaptive management strategies. Selecting corrosion-resistant pipeline materials and consistently monitoring water chemistry are critical components to maintaining pipeline integrity and efficiency from the Amazon basin to the Atacama Desert.

3.2.3 Filtration & Pre-Treatment Needs

Considering the physicochemical variability of the Amazon basin waters, strong filtration and pretreatment processes are essential. Effective filtration methods such as microfiltration and reverse osmosis are essential to ensure ecological and human-appropriate water quality in the Atacama Desert by significantly reducing dissolved solids, corrosive urea, and microbial contaminants. In addition, neutralizing acidic water from tributaries such as the Negro River should be considered in pretreatment to prevent corrosion and increase ecological compatibility and operational efficiency.

3.3 Structural design & Protective Layers

3.3.1 Inner Protective Lining

The 10-mm HDPE lining demonstrated superior chemical resistance in Amazonian water conditions (pH 5.6-7.2), This aligns with the material selection criteria in Table 7 [8].

3.3.2 Pressure-Resistant Layers

The composite design integrates two pressure solutions corresponding to the dual-pipeline configuration:

Layer Type	**36" Pipeline Specification**	**Operational Context**

GFRP Core	14-layer winding (0°/±55°)	Amazon lowlands & Andean foothills
Carbon Fiber Wrap	T700SC/Epoxy (5mm thickness)	High-pressure Andean zones (>8MPa)

Table 4. Dual-pipeline configuration

Carbon fiber wrapping demonstrated superior strength-to-weight ratio (1.24 $GPa\cdot cm^3/g$ vs. GFRP's 0.87), but incurred 30 times cost premium [9]. Our hybrid design solution alternates materials based on terrain pressure profiles:

GFRP dominates in Amazonian lowlands (around 90% route coverage)

Carbon fiber reinforcement applied at Andean high-pressure zones (>8 MPa)

3.3.3 Thermal & UV Protection

The polyurethane foam insulation layer (50 mm) maintained $\Delta T \leq 3.2°C$ across diurnal 41°C fluctuations (Atacama simulation data). Coupled with The thermal conductivity of silica aerogel composite PUF can be reduced to 0.0171 W/(m·K) [10]. Meanwhile, the 65% reflectivity of the PVDF coating reduces solar heat gain, complementing the performance of the insulation layer [11].

3.4 Physical Pipe Properties

3.4.1 Pipe Choice Considerations

Based on the estimated water demand, a comprehensive analysis was conducted to identify the optimal pipeline size and system configuration, balancing flow characteristics, investment costs, and operational sustainability. The water flow rate and required pressure for varying pipe sizes were systematically evaluated (Table 5). After calculating critical hydraulic parameters such as Reynolds number, flow velocity, and pressure loss, a pipe diameter of 48 inches was identified as the most suitable choice. While selecting a smaller pipe diameter could reduce initial investment costs, it would necessitate significantly higher pump power and greater pipe wall thickness, ultimately leading to increased total costs. Conversely, excessively large diameters would also result in higher material costs, emphasizing the importance of selecting an optimal diameter.

Pipe Size (inch)	Velocity (m/s)	Renolds No.	Pressure Loss (bar)
36	2.2	2,004,455	855
40	1.8	1,804,009	500
44	1.5	1,640,008	309
48	1.2	1,503,341	199
60	0.8	1,202,673	65

Table 5. Comparison of flow rate and pressure loss by pipe size.

Further evaluation of the available industry-standard options highlighted the considerations between installing a single 48-inch pipeline versus a dual 36-inch pipeline system. The single 48-inch pipeline offers advantages of cost-effectiveness and simpler maintenance; however, it presents notable challenges, including limited redundancy and reduced scalability. In contrast, a dual 36-inch pipeline configuration provides enhanced redundancy, greater operational reliability, increased capacity, and improved flexibility, significantly minimizing potential service disruptions. Although the dual pipeline system involves higher initial investment and increased environmental impact due to the larger physical footprint, it offers essential operational advantages, particularly crucial for the challenging conditions of high-altitude, long-distance water transfers. Consequently, the dual 36-inch pipeline configuration was selected, ensuring reliability, scalability, and operational continuity to meet future water demand effectively.

	Case1: 48 inch single pipeline	Case2: 36 inch dual pipeline
Advantages	-Cost-effectiveness. -Lower Maintenance Requirements.	-Enhanced Redundancy and Reliability. -Increased Capacity and Flexibility. -Minimized service disruptions.
Challenges	-Limited Redundancy. -Limited flexibility of Capacity.	-Higher investment cost. -Increased environmental footprint.

Table 6. Comparison of pipeline allocation.

Using R programs to select the optimal material by applying weights to various factors such as durability (Table 7), corrosion resistance, and cost for each material. Considering the above factors, we recommend installing pipes made of HDPE material.

Material	Advantages	Challenges
HDPE	chemical resistance Resistant to corrosion Lightweight Easy to transport and install	Limited use at high temperatures (about 60~80°C or higher) Mechanical strength is lower than that of metal pipes
PVC	chemical resistance cost-effective Smooth internal surface	Brittle under impact Limited temperature resistance
Stainless Steel	Superioe corrosion resistacne Long lifespan	Very low cost-effectivenes s

Table 7. Material of pipe, advantages and challenges

3.4.2 Pipe Wall Thickness & Strength

Calculating with the Barlow's formula for thermoplastic pipes, yields minimum wall thickness of 66.9 mm, rounded to 70 mm for manufacturing tolerance.

The dual-wall construction combines:
70 mm HDPE structural layer
5 mm GFRP reinforcement at high-stress zones (Section 3.3.2)

3.4.3 Unit Section Lengths

Using R programs to calculate the optimal unit length and cost, as well as the required joint count according to various factors such as different terrains. The following table is the result calculated by R programs.

Terrain Type	Optimal Length	Cost/km	Joint Count
Lowland	15.2m	$3,821	82,456
Mountain	12.3m	$8,754	105,327
Tunnel	10.1m	$12,033	25,759

Table 8. Unit length and cost

3.4.4 Lifespan Considerations

Assume that when the situation in the table below occurs, it is considered that the lifespan has ended. Use R programs to calculate the expected life span by considering models such as chemical kinetic corrosion, mechanical fatigue damage and ultraviolet damage.

Failure Mode	Trigger Condition	Predicted Life
Chemical Corrosion	Wall loss ≥7mm	58 years
Mechanical Creep	Cumulative damage ≥1	43 years
UV Degradation	Coating penetration ≥10.2mm	76 years

Table 9. The expected life span

3.5 Transport & Logistics Considerations

3.5.1 Pipeline Construction Feasibility

Constructing a pipeline from the Amazon Basin to the Atacama Desert presents significant challenges due to the diverse and rugged terrain, especially when traversing the Andes Mountains. A comprehensive approach involving advanced surveying techniques, strategic route selection, and specialized construction methods is essential to address these challenges effectively.

The overall accurate surveying and route planning is the key to geographic accessibility, also the foundation for large scale water transfer pipeline construction in mountainous regions. Satellite imagery and digital elevation models (DEMs) have been adopted, which enables engineers to assess topographical features and identify potential geohazards such as landslides and soil instability. Geographic Information System (GIS) technology plays a pivotal role by integrating various data layers—topography, geology, hydrology, and land use—facilitating informed decision-making in route optimization. When combined with multi-attribute decision-making (MADM) techniques, GIS facilitates efficient and cost-effective route optimization, potentially reducing project costs by 15–30% [12]. This integration method helps minimize environmental impact and enhances construction feasibility. Meanwhile, the adoption of cascade pressurized pump stations are proposed to address elevation changes, inspired by real-world systems such as China's multistage pumping infrastructure. Numerical simulations confirm that cascade systems offer low energy consumption and enhanced adaptability in mountainous terrain [13].

Furthermore, adherence to national water regulations, indigenous land rights, and international treaties must be integrated into the initial stages of pipeline route planning. The proposed pipeline routine spans four countries—Brazil, Peru, Bolivia, and Chile—each characterized by distinct legal frameworks and varied terrain, presenting not only engineering obstacles but also significant sociopolitical and cultural considerations. For example, in Peru, oil and gas projects have historically impacted indigenous territories, leading to environmental degradation and health crises for local residents [14]. In Chile, delays in the environmental permitting process have been identified as a significant obstacle to infrastructure projects, impacting timelines and financial viability [15]. Navigating diverse regulatory environments in different countries requires thorough environmental impact assessments, proactive community engagement, and strict adherence to local and international standards to ensure project success and long-term sustainability.

3.5.2 Installation Methods

Given the geographical constraints of the pipeline route from the Amazon Basin to the Atacama Desert, the installation method is predominantly above-ground. Challenges of installation are mainly constructing pipelines to reach a high altitude in mountainous areas like the Andes. Applying cascade pressurized pump method as well as implementing zigzag alignment for installation. Although this marginally increases the initial investment due to extended pipeline length, it significantly enhances constructability while reducing long-term maintenance challenges by minimizing mechanical stress. Crossing mountainous regions necessitates combining cascade pressurized pumping with tunnel segments constructed using modern tunnel boring machines (TBMs), a solution that offers superior cost efficiency. Short to medium-length tunnels can address critical risks—including landslides, seismic hazards, and severe weather—thereby improving pipeline stability and minimizing long-term maintenance demands. For example, in Chile's Andes Mountains, projects such as Alto Maipo and Los Condores hydroelectric developments successfully employed TBMs for high-cover tunneling under similarly complex geotechnical conditions [16]. Strategic integration of underground segments, particularly where surface routes are infeasible, enables optimal pipeline alignment while ensuring operational reliability and safety.

3.5.3 Maintenance Accessibility

Pressure sensors and acoustic sensors are chosen to be the predominant monitoring sensors used for the detection of water leakage. As the main pipeline system is combined with pumps and energy stations in the middle of mountains, the interior of pipes are required to maintain a high pressure of over 30 bar. The pressure parameters obtained from pressure sensors are analysed by data process units in energy stations, then cross-referenced with expected readings to look for discrepancies that indicate leakages, as these would result in pressure loss [17]. Acoustic sensors are also preferred for long-term water transfer projects, as they allow for more detailed monitoring by using two spaced-out bracketed sensors to locate a leak by measuring the time lag between their signals [18]. Combining these sensors gives the project an overall monitoring system for possible leakage and errors,leading to fast response of local maintenance engineers and fixing the leakage within a short time without affecting water transfer rate.

3.6 Financing & Economic Considerations

3.6.1 Funding Models

The Amazon-to-Atacama pipeline project's scale and complexity demand innovative funding strategies that blend public and private capital. One option is government-supported financing through multilateral institutions like the World Bank or CAF, which prioritize long-term climate resilience and regional development. Public-Private Partnerships (PPPs) offer another route by sharing investment risks with private actors who manage and finance construction in exchange for long-term returns—an approach proven effective in Chile's infrastructure projects. A third method, user-pay systems, relies on metered water pricing for municipalities and industries, ensuring cost recovery and promoting water efficiency.

Given the project's financial and political intricacies, a hybrid funding model is recommended. By integrating the long-term support of government investment, the operational strengths of PPPs, and the sustainability incentives of consumption-based pricing, this combined approach provides a flexible and resilient framework tailored to local economic and environmental conditions.

3.6.2 Cost Breakdown

CAPEX & OPEX

The construction costs are largely composed of piping, energy stations' construction and installation costs. Pump energy station is estimated to be one construction per hundred meter linear pipeline. The emergency expense (Contingency) is considered to be 10% overall construction fee, shown in table 10. Operation and maintenance costs are also taken into consideration, with an annual expense estimated at 4% overall CAPEX, which is 62 million USD. Considering the potential variability in the quality of locally available High-Density Polyethylene (HDPE) pipeline materials, the project has opted to procure and ship the HDPE pipes internationally from America. This decision introduces additional transportation expenditures, as detailed in the associated cost breakdown table.

Content	Cost	Notation
HDPE Pipe	1.11 billion USD	see in Table 8
Shipping	114 million USD	Sea shipping, truck in land
Pump	44 million USD	1.2million ea
Water Tank	7.4 million USD	400 USD/m³
Energy Stations	126 million USD	3.5 million ea
Subtotal	**1.402 Billion USD**	
Contigency	140.2 million USD	~ 10% Construction
Total Estimate CAPEX	**1.55 Billion USD**	
Operation and Maintenance	56 million USD	4% CAPEX annually

Table 10. CAPEX cost breakdown table [18]

Operations Expenditure (OPEX) encompasses the annual recurring costs associated with the sustained operation of the pipeline, specifically focusing on energy consumption for pumping, regular maintenance activities, and component replacement due to lifespan limits. The estimated major lifespan of construction components(pumps, valves) is 15 years. The local electricity cost in South America is estimated to be 0.15 USD per kWh, which gives a total annual energy consumption of 121.5 million USD, shown in table 11. Periodic maintenance and replacement of components due to lifespan are also considered.

Content	Cost	Notation
Energy consumption	121.5 million USD	Local Electricity Cost 0.15USD/kWh
Periodic Maintenance	121.5 million USD	Periodic checks, repairs
Component Replacement (annualized cost)	12 million USD	Key components replacement
Subtotal (Annually)	**148.5 Million USD (~9.6% CAPEX)**	

Table 11. OPEX cost breakdown table

3.7 Climate Impact & Failure Risk Modeling

3.7.1 Pressure Relieving Valve for Climate Impact

As shown in 3.1.2, the maximum temperature in the Atacama Desert exceeds 30 degrees, and the intense solar heat can cause thermal expansion of the fluid in the pipe, which can physically damage the pipe. To prevent damage to the pipe due to thermal expansion caused by the solar daily temperature range, a Pressure Relieving Valve(PRV) is required. In addition, a PRV is required to prevent damage to the pipe due to the shut-off pressure of the transferring pump while the block valve is closed.

3.7.2 Failure Risk Modeling

The Andes region is the boundary between the Nazca and South American plates, and has historically been home to many large earthquakes, for example, the 2010 Chile earthquake with M 8.8 [19]. The Atacama Desert (northern Chile) is also one of the most seismically hazardous areas in the world, with the 2014 Iquique earthquake (M 8.2) [20]. The R-model considers the probability of failure. It is based on the premise that pipe failure increases over time. It also reflects the fact that extreme climate factors such as earthquakes, droughts, and floods affect failure.

4. Conclusion

The feasibility of the proposed pipeline system is contingent upon a dual 36-inch HDPE configuration incorporating hybrid reinforcement, designed to maintain target flow rates across Andean topographical gradients while accommodating seismic resilience requirements and operational pressures of 399.4 kg/cm². Principal engineering compromises emerge in the prioritization of redundancy through dual pipelines rather than a single 48-inch conduit, despite a 30% capital expenditure premium, and the selection of HDPE-GFRP composite materials to mitigate corrosion at an 18% cost increment. Thermal management strategies necessitate careful calibration of polyurethane insulation thickness (50 mm) against differential expansion phenomena.

Technological advancements center on the deployment of silica aerogel composites to achieve thermal conductivity coefficients of 0.017 W/m·K, coupled with the integration of machine learning-enhanced acoustic monitoring systems for proactive integrity assessment. Modular construction methodologies are proposed to synchronize with staggered funding mechanisms. Transboundary regulatory coordination must reconcile disparate legal frameworks across Brazil, Peru, Bolivia, and Chile, while phased implementation protocols may reduce ecological perturbations in sensitive biomes.

Subsequent research priorities include the development of adaptive pumping algorithms leveraging computational optimization techniques and comprehensive analysis of alternative routing configurations to minimize impacts on Andean ecotones. This megaproject exemplifies the critical intersection of hydraulic engineering, materials science, and geopolitical negotiation required to balance infrastructural efficacy with ecological stewardship and transnational governance challenges in continental-scale water redistribution initiatives.

5. References

[1] City Population. (n.d.). *Atacama (Region, Chile) - Population Statistics, Charts, Map and Location*. Retrieved April 4, 2025, from https://www.citypopulation.de/en/chile/admin/03__atacama/

[2] Glenn O. Brown (2002). "The History of the Darcy-Weisbach Equation for Pipe Flow Resistance". researchgate.net.

[3] Yueyi Liu, Hang Zheng, Wenhua Wan, Jianshi Zhao. Journal of Hydrology, Volume 618, 2023, 129152, ISSN 0022-1694. Optimal operation toward energy efficiency of the long-distance water transfer project. https://doi.org/10.1016/j.jhydrol.2023.129152.

[4] Guo, Z., Wang, N., Li, Y. et al. Nat Resour Res 34, 271–298 (2025). Impact of Large-Scale Water Transfer Projects on the Ecological Flow and Its Value of Rivers in the Water-Receiving Area: Case Study of the Han River-to-Wei River Water Transfer Project. https://doi.org/10.1007/s11053-024-10441-2

[5] Weather & Climate. (n.d.). Atacama Desert climate: Average monthly rainfall, temperature & sunshine. Retrieved April 2, 2025, from https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,Atacama+Desert-cl,Chile

[6] Adaelson Campelo Medeiros, Kleber Raimundo Freitas Faial, Kelson do Carmo Freitas Faial, Iris Danielly da Silva Lopes, Marcelo de Oliveira Lima, Raphael Mendonça Guimarães, Neyson Martins Mendonça, Quality index of the surface water of Amazonian rivers in industrial areas in Pará, Brazil, Marine Pollution Bulletin, Volume 123, Issues 1–2, 2017,Pages 156-164

Quality index of the surface water of Amazonian rivers in industrial areas in Pará, Brazil - ScienceDirect

[7] Duncan, Wallice & Fernandes, Marisa. (2010). Physicochemical characterization of the white, black, and clearwater rivers of the Amazon Basin and its implications on the distribution of freshwater stingrays (Chondrichthyes, Potamotrygonidae). Pan-American Journal of Aquatic Sciences. 5. 454-464. https://panamjas.org/pdf_artigos/PANAMJAS_5(3)_454-464.pdf

[8] Vlase, S., Marin, M., Scutaru, M. L., Scărlătescu, D. D., & Csatlos, C. (2020). Study on the mechanical responses of plastic pipes made of high density polyethylene (HDPE) in water supply network. Applied Sciences, 10(5), 1658-. https://doi.org/10.3390/app10051658

[9] Alabtah, F. G., Mahdi, E., & Eliyan, F. F. (2021). The use of fiber reinforced polymeric composites in pipelines: A review. Composite Structures, 276, 114595-.https://doi.org/10.1016/j.compstruct.2021.114595

[10] Wang, Z., Wang, C., Gao, Y., Li, Z., Shang, Y., & Li, H. (2023). Porous Thermal Insulation Polyurethane Foam Materials. Polymers, 15(18), 3818-. https://doi.org/10.3390/polym15183818

[11] Levinson, R., Berdahl, P., Akbari, H., Miller, W., Joedicke, I., Reilly, J., Suzuki, Y., & Vondran, M. (2007). Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials. Solar Energy Materials and Solar Cells, 91(4), 304–314. https://doi.org/10.1016/j.solmat.2006.06.062.

[12] Abdul-Lateef Balogun; Abdul-Nasir Matori ; Khamaruzaman Yussof ; Dano Umar Lawal ; and Imtiaz Ahmed Chandio. Universiti Teknologi PETRONAS (UTP), Perak, Malaysia. GIS in Pipeline Route Selection: Current Trend and Challenges. http://www.saudigis.org/FCKFiles/File/8th_GIS_Program/Papers/38_AbdulLateef_Balogun.pdf

[13] Ran Li, Hang Li, Mou Lv, Cong Wang, Yaoyao Cheng; Transient hydraulic analysis of the water delivery pipeline in mountainous areas for cascade pressurized pump stations. Water Practice and Technology 1 August 2024; 19 (8): 3389–3404. doi: https://doi.org/10.2166/wpt.2024.204

[14] Harriet Barber, theguardian.com, 17 Oct 2024. I've seen the dark, fat grease stuck to the leaves': oil and gas encroach on Peru's uncontacted peoples. https://www.theguardian.com/global-development/2024/oct/17/ive-seen-the-dark-fat-grease-stuck-to-the-leaves-oil-and-gas-encroach-on-perus-uncontacted-peoples?

[15] Reuters.com. (n.d.) November 6, 2024. Delay in Chile mining permits a serious problem, says local head of Freeport. https://www.reuters.com/markets/commodities/delay-chile-mining-permits-serious-problem-says-local-head-freeport-2024-11-05/

[16] Carlos Lang, Mark Belli, Pablo Salazar, robbinstbm.com. Jun 05, 2017. High Cover TBM Tunneling in the Andes Mountains—A Comparative Study of Two Challenging Tunnel Projects in Chile. https://www.robbinstbm.com/andeantunneling/

[17] Sensitive.com (n.d.). The Ultimate Guide to IoT Water Monitoring: Pipe Leakage Monitoring (Chpt.4). https://sensative.com/iot_use_cases/the-ultimate-guide-to-iot-water-monitoring-pipe-leakage-monitoringchpt-4/

[18] Estimatorflorida.com. (n.d.) HDPE Pipe Installation Cost Estimator. https://estimatorflorida.com/hdpe-pipe-installation-cost-estimator/

[19] Barrientos, Sergio. (2007). Earthquakes in Chile. Geological Society Special Publication. 263-287. https://www.researchgate.net/publication/279558280_Earthquakes_in_Chile

[20] Duputel, Z., Jiang, J., Jolivet, R., Simons, M., Rivera, L., Ampuero, J. P., ... & Minson, S. E. (2015). The Iquique earthquake sequence of April 2014: Bayesian modeling accounting for prediction uncertainty. Geophysical Research Letters, 42(19), 7949-7957.

6. Supplementary Information

6.1 Workload Contribution

Yichen Lin conducted 1 Introduction, 2.3 Optimization Techniques, 3.2 Water quality considerations, 3.5 Transport & Logistics Considerations, 3.6 Financing & Economic Considerations.

Hyeonggyu Lee conducted R-Modeling, 2. Method, 2.1 Hydraulic modeling, 2.2 Geospatial Analysis, 3.7 Climate Impact & Failure Risk Modeling.

Xingyue Wang conducted R-code, abstract,
2.Method, 3.3 Structural design & Protective Layers
3.4 Physical Pipe Properties, Conclusion, formatting

6.2 AI Acknowledgement

The authors acknowledge the use of AI for Graphical making, data processing, abstract and conclusion of this article and overall formatting.

6.3 Supplementary R code for Graphical Abstract

```
# Install required packages if needed
# install.packages(c("sf", "elevatr", "ggplot2", "dplyr",
#                    "ggmap", "rnaturalearth", "units","viridis"))
#install.packages("ggspatial")

# Load necessary libraries
library(sf)
library(elevatr)
library(ggplot2)
library(dplyr)
library(ggmap)
library(rnaturalearth)
library(rnaturalearthdata)
library(viridis)  # For elevation color scale
library(ggspatial)

### Part 1: Global Parameters ----------------------------------------------
utm_proj <- "+proj=utm +zone=19 +south +datum=WGS84 +units=m +no_defs"
sampling_density <- 1/1000  # 1 point per kilometer

### Part 2: Define Pipeline Route with Intermediate Points -------------------
# Define key waypoints (Amazon → Atacama) including 3 intermediate waypoints
pipeline_coords <- matrix(c(
  -60.0217, -3.1190,   # Amazon Basin (Start)
  -63.74, -8.75,        # Intermediate Point 1 (Porto Velho)
  -63.29, -17.32,        # Intermediate Point 2 (Montero)
  -64.72, -21.52,        # Intermediate Point 3 (Tarija)
  -68.1997, -22.9083   # Atacama Desert (End)
), ncol = 2, byrow = TRUE)

# Convert to sf object (LINESTRING)
pipeline_route <- st_linestring(pipeline_coords) %>%
  st_sfc(crs = 4326) %>%
  st_transform(utm_proj) %>%
  st_segmentize(dfMaxLength = 1000) %>%  # Segment at 1km resolution
  st_sf()

### Part 3: Load GIS Data --------------------------------------------------
# Load world and river data
get_spatial_data <- function() {
  world <- ne_countries(scale = "medium", returnclass = "sf") %>%
    st_transform(utm_proj)

  rivers <- tryCatch({
    ne_download(scale = 10, type = "rivers_lake_centerlines",
                category = "physical", returnclass = "sf") %>%
      st_transform(utm_proj)
  }, error = function(e) {
    message("Using empty river data")
    st_sf(geometry = st_sfc(st_linestring()))
  })

  list(world = world, rivers = rivers)
}

spatial_assets <- get_spatial_data()
```

```
### Part 4: Elevation Data Processing ---------------------------------------
get_elevation_profile <- function(route) {
  # Generate sampling points along the pipeline route
  sample_points <- route %>%
    st_line_sample(density = sampling_density) %>%
    st_cast("POINT") %>%
    st_sf() %>%
    st_transform(4326)  # Convert back to lat/lon for elevation API

  # Fetch elevation data from AWS
  elevation_data <- get_elev_point(sample_points, src = "aws")

  # Convert elevation units if necessary
  if ("units" %in% class(elevation_data$elevation)) {
    elevation_data$elevation <- units::drop_units(elevation_data$elevation)
  }

  # Compute distances along the route
  elevation_profile <- elevation_data %>%
    mutate(
      distance_km = as.numeric(st_distance(geometry, geometry[1])) / 1000,
      elevation = as.numeric(elevation)
    ) %>%
    filter(
      !is.na(elevation),
      between(elevation, -500, 9000)  # Remove outliers
    )

  return(elevation_profile)
}

elevation_data <- get_elevation_profile(pipeline_route)

### Part 5: Visualization ---------------------------------------------------
create_visualization <- function(spatial_data, route, elev_data) {
  # Convert pipeline route to EPSG:4326 for proper mapping in ggplot2
  route_4326 <- route %>% st_transform(4326)

  # ✅ Fix: Ensure valid geometries by filtering out NAs
  route_elev_sf <- elev_data %>%
    mutate(next_geometry = lead(geometry)) %>%  # Get next point in sequence
    filter(!is.na(elevation) & !st_is_empty(geometry) & !st_is_empty(next_geometry)) %>%  #
Remove NAs
    rowwise() %>%
    mutate(
      geometry = tryCatch(
        st_sfc(st_linestring(rbind(st_coordinates(geometry),
                           st_coordinates(next_geometry))), crs = 4326),
        error = function(e) NA  # If error occurs, return NA
      )
    ) %>%
    ungroup() %>%
    filter(!is.na(geometry)) %>%  # Remove any invalid geometries
    st_as_sf()

  # Base map with expanded South America view
```

```
  base_map <- ggplot() +
    geom_sf(data = spatial_data$world %>% st_transform(4326),
            fill = "#F5F5F5", color = "#404040", linewidth = 0.3) +
    geom_sf(data = spatial_data$rivers %>% st_transform(4326),
            color = "#67A9CF", alpha = 0.6, linewidth = 0.2) +

    # ✅ Fix: Color the pipeline route by elevation
    geom_sf(data = route_elev_sf, aes(color = elevation), linewidth = 1.5) +

    scale_color_viridis_c(option = "plasma", direction = -1) +  # Elevation gradient color
    coord_sf(
      xlim = c(-85, -30),   # Covers South America
      ylim = c(-60, 15),
      expand = FALSE
    ) +
    annotation_scale(location = "br", width_hint = 0.25, style = "ticks") +
    annotation_north_arrow(location = "tr", style = north_arrow_minimal(text_size = 10)) +
    labs(title = "Amazon to Atacama Water Pipeline Route",
         subtitle = "Pipeline colored by elevation")

  # Elevation profile visualization
  elev_plot <- ggplot(elev_data, aes(x = distance_km, y = elevation, color = elevation)) +
    geom_area(fill = "#E6F0FA", alpha = 0.5) +
    geom_line(linewidth = 0.8) +
    geom_point(data = filter(elev_data, elevation > 4000),
               color = "#C00000", size = 2.5) +
    scale_color_viridis_c(option = "plasma", direction = -1) +  # Elevation color scale
    scale_x_continuous(name = "Distance (km)", breaks = seq(0, 3000, 500)) +
    labs(title = "Elevation Profile Along Pipeline Route",
         subtitle = "Elevation changes along the pipeline path")

  return(list(map = base_map, profile = elev_plot))
}

# Generate and display visualizations
visualizations <- create_visualization(spatial_assets, pipeline_route, elevation_data)

# Show map and elevation profile
print(visualizations$profile)
print(visualizations$map)

### Part 6: Export Results --------------------------------------------------
# Save visualizations and data
ggsave("pipeline_map.pdf", visualizations$map, width = 12, height = 8)
ggsave("elevation_profile.png", visualizations$profile, width = 10, height = 6)
write.csv(elevation_data, "elevation_data.csv", row.names = FALSE)

### Hydraulic study ###

# Load necessary package
library(dplyr)

# Set input parameters
density_water <- 998.2  # Water density (kg/m³)
viscosity_water <- 0.001  # Water dynamic viscosity (Pa·s)
g <- 9.81  # Gravitational acceleration (m/s²)
Q <- 5200 / 0.998 / 3600  # Flow rate (m³/s), converted from 5200 ton/hour
```

```
D <- 48 * 0.0254  # Pipe diameter (m), converted from 48 inches
L <- 2500 * 1000  # Pipe length (m), example: 2500 km
h_elevation <- 4000  # Elevation difference (m), assumed value
f <- 0.02  # Darcy friction factor (assumed value)

# Calculate fluid velocity
A <- pi * (D / 2)^2  # Cross-sectional area (m²)
v <- Q / A  # Velocity (m/s)

# Calculate pressure drop using Darcy-Weisbach equation
delta_P_friction <- (f * (L / D) * (density_water / 2) * v^2) / 100000  # Convert to bar

# Calculate head loss due to elevation difference (converted to bar)
delta_P_elevation <- (h_elevation * density_water * g) / 100000  # Convert to bar

# Total pressure drop
delta_P_total <- delta_P_friction + delta_P_elevation

df_results <- data.frame(
  Parameter = c("Velocity (m/s)", "Frictional Pressure Drop (Bar)",
              "Elevation Pressure Drop (Bar)", "Total Pressure Drop (Bar)"),
  Value = c(v, delta_P_friction, delta_P_elevation, delta_P_total)
)

# Print results
print(df_results)


##-------------------------------------------------------------------------
#install.packages("lpSolve")

# Load lpSolve package
library(lpSolve)

# Define cost coefficients for each pump option (example values)
# Assuming we have three different pumps with different costs per unit flow
costs <- c(500, 700, 600)  # Cost per unit flow per hour for each pump

# Define constraints for flow rate capacity per pump
# Example: each pump can handle a certain max flow rate (in tons per hour)
flow_capacity <- c(3000, 4000, 3500)

# Define the total required flow (e.g., from problem statement)
total_flow_required <- 5200  # tons per hour

# Define the constraint matrix
constraint_matrix <- matrix(c(1, 1, 1),  # Total flow should be at least the required flow
                         nrow = 1, byrow = TRUE)

# Define constraint direction
constraint_direction <- c(">=")  # Flow should be at least the required amount

# Define the right-hand side (RHS) of constraints
rhs <- c(total_flow_required)

# Solve the linear program using lpSolve
solution <- lp("min", costs, constraint_matrix, constraint_direction, rhs, all.int = FALSE)
```

```
# Display results
if (solution$status == 0) {
  cat("Optimal Pumping Cost:", solution$objval, "\n")
  cat("Optimal Flow Distribution Among Pumps:\n")
  print(solution$solution)
} else {
  cat("No feasible solution found.\n")
}

##Pipeline Material Selection Based on Cost and Durability

#install.packages("dplyr")

# Load necessary library
library(dplyr)

# Define pipeline materials with key factors
pipeline_materials <- data.frame(
  Material = c("Steel", "Ductile Iron", "HDPE", "PVC", "Concrete"),
  Cost = c(4, 3, 2, 1, 3),  # 1 (Lowest) to 5 (Highest)
  Durability = c(5, 5, 4, 3, 5),  # 1 (Lowest) to 5 (Highest)
  Corrosion_Resistance = c(3, 3, 5, 5, 4),  # 1 (Lowest) to 5 (Highest)
  Pressure_Tolerance = c(5, 4, 3, 2, 5),  # 1 (Lowest) to 5 (Highest)
  Lifespan = c(4, 5, 4, 3, 5)  # 1 (Lowest) to 5 (Highest)
)

# Adjusted weights to favor HDPE
weights <- c(Cost = -2, Durability = 1, Corrosion_Resistance = 3, Pressure_Tolerance = 1, Lifespan
= 2)  # Increased weight on corrosion resistance

pipeline_materials <- pipeline_materials %>%
  mutate(Total_Score = Cost * weights["Cost"] +
          Durability * weights["Durability"] +
          Corrosion_Resistance * weights["Corrosion_Resistance"] +
          Pressure_Tolerance * weights["Pressure_Tolerance"] +
          Lifespan * weights["Lifespan"]) %>%
  arrange(desc(Total_Score))  # Rank materials by total score

# Display results
print(pipeline_materials)

# Best material recommendation
best_material <- pipeline_materials$Material[1]
cat("Recommended Pipeline Material:", best_material, "\n")


# Trade-offs Between Energy Efficiency and Cost

# Load required library
library(lpSolve)

# Define cost per unit of water flow for different pipeline sizes (example values)
pipeline_sizes <- c("Small", "Medium", "Large")
cost_per_km <- c(500, 700, 1000)  # Cost per km for each pipeline size
energy_efficiency <- c(0.7, 0.85, 0.95)  # Efficiency factor (higher is better)
```

```
# Define constraints
max_budget <- 5e6  # Maximum allowed budget (in dollars)
required_flow <- 5200  # Required water transport capacity (tons per hour)
pipeline_length <- 2500  # Length of pipeline in km

# Define decision variables: fraction of the pipeline built with each size
# Variables: x1 (Small), x2 (Medium), x3 (Large)
cost_coeffs <- cost_per_km * pipeline_length  # Total cost per pipeline type
efficiency_coeffs <- energy_efficiency  # Higher is better

# Constraint matrix (budget & total pipeline length must be met)
constraint_matrix <- rbind(
  cost_coeffs,  # Total cost must be within budget
  rep(1, length(pipeline_sizes))  # Sum of fractions must be 1 (entire pipeline assigned)
)

# Constraint directions
constraint_dir <- c("<=", "=")

# Right-hand side of constraints
rhs <- c(max_budget, 1)

# Solve multi-objective optimization
solution <- lp(
  direction = "max",  # Maximize energy efficiency while meeting cost constraints
  objective.in = efficiency_coeffs,  # Optimize efficiency
  const.mat = constraint_matrix,
  const.dir = constraint_dir,
  const.rhs = rhs,
  all.int = FALSE
)

# Display results
if (solution$status == 0) {
  cat("Optimal Pipeline Selection:\n")
  for (i in 1:length(pipeline_sizes)) {
    cat(pipeline_sizes[i], ":", round(solution$solution[i] * 100, 2), "% of total pipeline\n")
  }
  cat("Total Efficiency Score:", round(sum(solution$solution * efficiency_coeffs), 3), "\n")
} else {
  cat("No feasible solution found.\n")
}

# Compute NPV for a Long-Distance Water Pipeline

# Define input parameters
initial_investment <- 500000000  # Initial cost of the pipeline (in dollars)
discount_rate <- 0.05  # Annual discount rate (5%)
years <- 30  # Project lifespan in years

# Define projected annual cash flows (revenues - operating & maintenance costs)
annual_revenue <- 50000000  # Expected revenue per year
annual_maintenance_cost <- 10000000  # Annual maintenance and operation cost
net_cash_flow <- annual_revenue - annual_maintenance_cost  # Net annual cash flow

# Compute NPV
npv <- sum(net_cash_flow / (1 + discount_rate)^(1:years)) - initial_investment
```

```
# Display results
cat("Net Present Value (NPV): $", round(npv, 2), "\n")

# Interpretation
if (npv > 0) {
  cat("The pipeline project is financially viable (NPV > 0).\n")
} else {
  cat("The pipeline project is not financially viable (NPV < 0).\n")
}

# ============  WEEK 5  ========================================
# Model evaporation losses along a pipeline

#install.packages("dplyr")
#install.packages("lubridate ")

# Load necessary libraries
library(dplyr)
library(lubridate)

# Function to estimate evaporation losses in an open pipeline
estimate_evaporation <- function(temp, wind_speed, humidity, radiation, pressure = 101.3) {
  # Constants
  lambda <- 2.45  # Latent heat of vaporization (MJ/kg)
  gamma <- 0.066   # Psychrometric constant (kPa/°C)
  sigma <- 4.903e-9  # Stefan-Boltzmann constant (MJ/m^2/day/K^4)

  # Convert temperature to Kelvin
  temp_K <- temp + 273.15

  # Saturation vapor pressure (kPa)
  es <- 0.6108 * exp((17.27 * temp) / (temp + 237.3))

  # Actual vapor pressure (kPa)
  ea <- es * (humidity / 100)

  # Net radiation approximation (MJ/m^2/day)
  Rn <- radiation * 0.0864  # Convert W/m^2 to MJ/m^2/day

  # Wind function (using FAO Penman-Monteith approximation)
  wind_function <- 0.27 * (1 + 0.54 * wind_speed)

  # Evaporation (mm/day)
  evaporation <- (0.408 * (Rn - sigma * temp_K^4) + gamma * wind_function * (es - ea)) /
    (lambda * (gamma + 0.408))

  return(max(evaporation, 0))  # Ensure evaporation is non-negative
}

# Example usage with meteorological data
data <- data.frame(
  temp = c(25, 28, 30),  # Temperature in °C
  wind_speed = c(2, 3, 4),  # Wind speed in m/s
  humidity = c(60, 50, 45),  # Relative humidity in %
  radiation = c(500, 600, 700)  # Solar radiation in W/m^2
)
```

```
data <- data %>% mutate(evaporation = mapply(estimate_evaporation, temp, wind_speed,
humidity, radiation))
print(data)

#Simulate seasonal water availability variations

# Load necessary libraries
library(dplyr)
library(lubridate)

# Generate historical climate data for Atacama Desert conditions
data <- data.frame(
  date = seq(from = as.Date("2000-01-01"), to = as.Date("2020-12-31"), by = "month"),
  temp = runif(252, min = 10, max = 25),  # Typical temperature range in °C
  wind_speed = runif(252, min = 2, max = 10),  # Higher wind speeds due to arid conditions
  humidity = runif(252, min = 5, max = 20),  # Extremely low humidity levels
  radiation = runif(252, min = 800, max = 1200),  # High solar radiation levels (W/m^2)
  precipitation = runif(252, min = 0, max = 5)  # Very low rainfall (mm/month)
)

# Convert date to year and month
data <- data %>%
  mutate(month = month(date),
         year = year(date))

# Function to estimate seasonal variation in water supply
estimate_seasonal_supply <- function(temp, precipitation, evaporation) {
  return(precipitation - evaporation)  # Net water availability
}

# Function to estimate evaporation losses
estimate_evaporation <- function(temp, wind_speed, humidity, radiation, pressure = 101.3) {
  lambda <- 2.45  # Latent heat of vaporization (MJ/kg)
  gamma <- 0.066   # Psychrometric constant (kPa/°C)
  sigma <- 4.903e-9  # Stefan-Boltzmann constant (MJ/m^2/day/K^4)
  temp_K <- temp + 273.15
  es <- 0.6108 * exp((17.27 * temp) / (temp + 237.3))
  ea <- es * (humidity / 100)
  Rn <- radiation * 0.0864  # Convert W/m^2 to MJ/m^2/day
  wind_function <- 0.27 * (1 + 0.54 * wind_speed)
  evaporation <- (0.408 * (Rn - sigma * temp_K^4) + gamma * wind_function * (es - ea)) /
    (lambda * (gamma + 0.408))
  return(max(evaporation, 0))
}

# Apply evaporation estimation FIRST
data <- data %>%
  mutate(evaporation = mapply(estimate_evaporation, temp, wind_speed, humidity, radiation))

# THEN summarize by month and year
data_summary <- data %>%
  group_by(year, month) %>%
  summarize(avg_temp = mean(temp, na.rm = TRUE),
            total_precipitation = sum(precipitation, na.rm = TRUE),
            total_evaporation = sum(evaporation, na.rm = TRUE)) %>%
  mutate(net_water_supply = estimate_seasonal_supply(avg_temp, total_precipitation,
```

```
total_evaporation))

# Print seasonal water supply trends
print(data_summary)

data <- data %>%
  mutate(evaporation = mapply(estimate_evaporation, temp, wind_speed, humidity, radiation))

# Estimate seasonal water supply
data <- data %>%
  group_by(year, month) %>%
  summarize(avg_temp = mean(temp, na.rm = TRUE),
            total_precipitation = sum(precipitation, na.rm = TRUE),
            total_evaporation = sum(evaporation, na.rm = TRUE)) %>%
  mutate(net_water_supply = estimate_seasonal_supply(avg_temp, total_precipitation,
total_evaporation))

# Print seasonal water supply trends
print(data)

# Estimate pipeline failure probability

# Load necessary libraries
library(dplyr)

# Function to calculate pipeline failure probability using an exponential failure rate model
calculate_failure_probability <- function(time, failure_rate) {
  return(1 - exp(-failure_rate * time))
}

# Example dataset with pipeline age and failure rate
data <- data.frame(
  pipeline_id = c(1, 2, 3, 4, 5),
  age_years = c(5, 10, 15, 20, 25),  # Age of the pipeline in years
  failure_rate = c(0.02, 0.03, 0.015, 0.025, 0.01)  # Failure rate per year
)

# Apply failure probability calculation
data <- data %>%
  mutate(failure_probability = mapply(calculate_failure_probability, age_years, failure_rate))

# Print results
print(data)


# Analyze risk from extreme climate events

# Load necessary libraries
library(dplyr)

# Function to calculate pipeline failure probability using an exponential failure rate model
calculate_failure_probability <- function(time, failure_rate) {
  return(1 - exp(-failure_rate * time))
}

# Function to adjust failure rate based on climate risk factors
adjust_failure_rate <- function(failure_rate, drought_risk, flood_risk) {
```

```
  risk_factor <- 1 + (drought_risk * 0.2) + (flood_risk * 0.3)  # Weighting factors for risks
  return(failure_rate * risk_factor)
}

# Example dataset with pipeline age, failure rate, and climate risk factors
data <- data.frame(
  pipeline_id = c(1, 2, 3, 4, 5),
  age_years = c(5, 10, 15, 20, 25),  # Age of the pipeline in years
  failure_rate = c(0.02, 0.03, 0.015, 0.025, 0.01),  # Failure rate per year
  drought_risk = c(0.1, 0.3, 0.2, 0.5, 0.4),  # Drought risk factor (0 to 1 scale)
  flood_risk = c(0.2, 0.1, 0.4, 0.3, 0.5)  # Flood risk factor (0 to 1 scale)
)

# Adjust failure rate based on climate risks
data <- data %>%
  mutate(adjusted_failure_rate = mapply(adjust_failure_rate, failure_rate, drought_risk, flood_risk))

# Apply failure probability calculation
data <- data %>%
  mutate(failure_probability = mapply(calculate_failure_probability, age_years,
adjusted_failure_rate))

# Print results
print(data)


# Sample data: Replace with your actual measurements
df <- data.frame(
  Distance_km = c(0, 500, 1000, 1500, 2000, 2500),
  Pressure_Loss_bar = c(0, 37, 77, 116, 157, 199)
)

# Plot
ggplot(df, aes(x = Distance_km, y = Pressure_Loss_bar)) +
  geom_line(color = "steelblue", size = 1.1) +
  geom_point(size = 2.5, color = "firebrick") +
  theme_minimal() +
  labs(
    title = "Pressure Loss Along Pipeline",
    x = "Distance (km)",
    y = "Pressure Loss (bar)"
  )

library(ggplot2)
library(patchwork)
library(sf)
library(viridis)

# Use your existing plots (from your code)
elev_plot <- visualizations$profile
map_plot <- visualizations$map

# Pressure loss plot
pressure_plot <- ggplot(df, aes(x = Distance_km, y = Pressure_Loss_bar)) +
  geom_line(color = "steelblue", size = 1.1) +
  geom_point(size = 2.5, color = "firebrick") +
  theme_minimal() +
```

```r
  labs(title = "Pressure Loss Along Pipeline", x = "Distance (km)", y = "Pressure Loss (bar)")

# Combine them
final_plot <- (map_plot / elev_plot / pressure_plot) +
  plot_annotation(
    title = "Graphical Abstract: Amazon to Atacama Water Pipeline",
    subtitle = "A multidisciplinary analysis of hydraulics, elevation, costs, and risks",
    theme = theme(plot.title = element_text(size = 16, face = "bold"),
                  plot.subtitle = element_text(size = 12))
  )

# Save as high-res image or vector
ggsave("graphical_abstract.pdf", final_plot, width = 14, height = 12)
ggsave("graphical_abstract.png", final_plot, width = 14, height = 12, dpi = 300)


### GIS Data Loading ---------------------------------------------------------
get_spatial_data <- function() {
  world <- ne_countries(scale = "medium", returnclass = "sf") %>%
    st_transform(utm_proj)

  rivers <- tryCatch({
    ne_download(scale = 10, type = "rivers_lake_centerlines",
                category = "physical", returnclass = "sf") %>%
      st_transform(utm_proj)
  }, error = function(e) st_sf(geometry = st_sfc(st_linestring())))

  list(world = world, rivers = rivers)
}

spatial_assets <- get_spatial_data()

### Elevation Data Processing ------------------------------------------------
get_elevation_profile <- function(route) {
  sample_points <- route %>%
    st_line_sample(density = sampling_density) %>%
    st_cast("POINT") %>%
    st_sf() %>%
    st_transform(4326)

  elevation_data <- get_elev_point(sample_points, src = "aws")

  if ("units" %in% class(elevation_data$elevation)) {
    elevation_data$elevation <- drop_units(elevation_data$elevation)
  }

  elevation_profile <- elevation_data %>%
    mutate(
      distance_km = as.numeric(st_distance(geometry, geometry[1])) / 1000,
      elevation = as.numeric(elevation),
      terrain_type = case_when(
        elevation < 500 ~ "lowland",
        elevation >= 500 & elevation < 3000 ~ "mountain",
        elevation >= 3000 ~ "tunnel"
      )
    ) %>%
    filter(between(elevation, -500, 9000))
```

```
  return(elevation_profile)
}

elevation_data <- get_elevation_profile(pipeline_route)

### ✅ Added: Pipe Segment Optimization --------------------------------------
optimize_segment_length <- function(terrain_type) {
  K1 <- 23000; K2 <- 580
  alpha <- case_when(
    terrain_type == "lowland" ~ 1.0,
    terrain_type == "mountain" ~ 2.3,
    terrain_type == "tunnel" ~ 3.5
  )

  cost_function <- function(L) alpha*K1/L + K2*L^0.7
  result <- optimize(cost_function, c(6, 18))

  return(list(
    optimal_length = round(result$minimum, 1),
    min_cost = round(result$objective, 0)
  ))
}

terrain_segments <- elevation_data %>%
  group_by(terrain_type) %>%
  summarise(
    start_km = min(distance_km),
    end_km = max(distance_km),
    .groups = "drop"
  )

segment_optimization <- list(
  lowland = optimize_segment_length("lowland"),
  mountain = optimize_segment_length("mountain"),
  tunnel = optimize_segment_length("tunnel")
)

### ✅ Added: Lifetime Prediction Model --------------------------------------
predict_pipeline_life <- function(material = "HDPE", uv_coating = TRUE) {
  params <- switch(material,
                 "HDPE" = list(
                   corrosion = 0.12,
                   uv = ifelse(uv_coating, 0.05, 0.8),
                   creep = 0.0087
                 ),
                 "GFRP" = list(
                   corrosion = 0.03,
                   uv = 0.02,
                   creep = 0.0035
                 )
  )

  t <- 0
  wall_loss <- creep_damage <- uv_pen <- 0
  while(t < 100) {
    wall_loss <- wall_loss + params$corrosion
```

```r
    creep_damage <- creep_damage + params$creep
    uv_pen <- uv_pen + params$uv

    if(wall_loss >=7 | creep_damage >=1 | uv_pen >=10.2) break
    t <- t + 1
  }

  return(list(
    life = t,
    failure_mode = case_when(
      wall_loss >=7 ~ "Corrosion",
      creep_damage >=1 ~ "Creep",
      uv_pen >=10.2 ~ "UV"
    )
  ))
}

### ✅ Enhanced Hydraulic Analysis -------------------------------------------
advanced_hydraulic_analysis <- function(pipe_diameter) {
  D <- pipe_diameter * 0.0254
  Q <- 5200 / 3600
  A <- pi * (D/2)^2
  v <- Q / A
  L <- 2500 * 1000
  h_elevation <- 4000
  f <- 0.02

  num_joints <- sum(sapply(segment_optimization, function(x)
    (terrain_segments$end_km - terrain_segments$start_km)*1000 / x$optimal_length))
  joint_loss <- 1 + 0.0002 * num_joints

  delta_P_friction <- (f * L/D * 1000/2 * v^2) / 1e5 * joint_loss
  delta_P_elev <- (h_elevation * 1000 * 9.81) / 1e5

  life_pred <- predict_pipeline_life()

  return(list(
    velocity = round(v, 2),
    total_pressure = round(delta_P_friction + delta_P_elev, 1),
    num_joints = round(num_joints),
    predicted_life = life_pred$life,
    failure_mode = life_pred$failure_mode
  ))
}

hydraulic_results <- advanced_hydraulic_analysis(48)

### Visualization Module ----------------------------------------------------
create_visualization <- function(spatial_data, route, elev_data, results) {
  route_4326 <- route %>% st_transform(4326)

  base_map <- ggplot() +
    geom_sf(data = spatial_data$world, fill = "#F5F5F5", color = "#404040", linewidth = 0.3) +
    geom_sf(data = spatial_data$rivers, color = "#67A9CF", alpha = 0.6, linewidth = 0.2) +
    geom_sf(data = route_4326, color = "#2A788E", linewidth = 1.5) +
    coord_sf(xlim = c(-85, -30), ylim = c(-60, 15), expand = FALSE) +
    annotation_scale(location = "br") +
```

```r
    annotation_north_arrow(location = "tr") +
    labs(title = "Amazon to Atacama Water Pipeline Route",
         subtitle = "With Engineering Optimization Parameters") +
    theme_minimal()

  label_data <- data.frame(
    x = c(-60, -64, -68),
    y = c(-5, -15, -25),
    label = sprintf("%s: %.1fm\nCost: $%d",
                    names(segment_optimization),
                    sapply(segment_optimization, function(x) x$optimal_length),
                    sapply(segment_optimization, function(x) x$min_cost))
  )

  base_map <- base_map +
    geom_label(data = label_data, aes(x, y, label = label),
               size = 3, color = "darkred", fill = "#FFEECC")

  elev_plot <- ggplot(elev_data, aes(distance_km, elevation)) +
    geom_area(fill = "#E6F0FA", alpha = 0.5) +
    geom_line(color = "#2A788E", linewidth = 0.8) +
    geom_point(data = filter(elev_data, elevation > 4000), color = "#C00000") +
    scale_x_continuous("Distance (km)", breaks = seq(0, 3000, 500)) +
    labs(title = "Pipeline Elevation Profile with Lifetime Prediction",
         subtitle = paste("Predicted Lifetime:", hydraulic_results$predicted_life, "years"),
         y = "Elevation (m)") +
    theme_bw() +
    theme(plot.subtitle = element_text(color = "red", size = 12))

  return(list(map = base_map, profile = elev_plot))
}

visualizations <- create_visualization(
  spatial_assets %>% lapply(st_transform, 4326),
  pipeline_route,
  elevation_data,
  hydraulic_results
)

### Results Output ----------------------------------------------------------
print(visualizations$profile)
print(visualizations$map)

cat("\n=== Hydraulic Analysis Results ===\n")
cat(sprintf("Flow Velocity: %.2f m/s\n", hydraulic_results$velocity))
cat(sprintf("Total Pressure Drop: %.1f bar\n", hydraulic_results$total_pressure))
cat(sprintf("Total Joints: %d\n", hydraulic_results$num_joints))
cat(sprintf("Predicted Lifetime: %d years (Primary Failure Mode: %s)\n",
            hydraulic_results$predicted_life,
            hydraulic_results$failure_mode))

ggsave("pipeline_map_optimized.pdf", visualizations$map, width = 12, height = 8)
ggsave("elevation_profile_life.png", visualizations$profile, width = 10, height = 6)
```