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Pipeline water transportation project: from Amazon basin to Atacama desert

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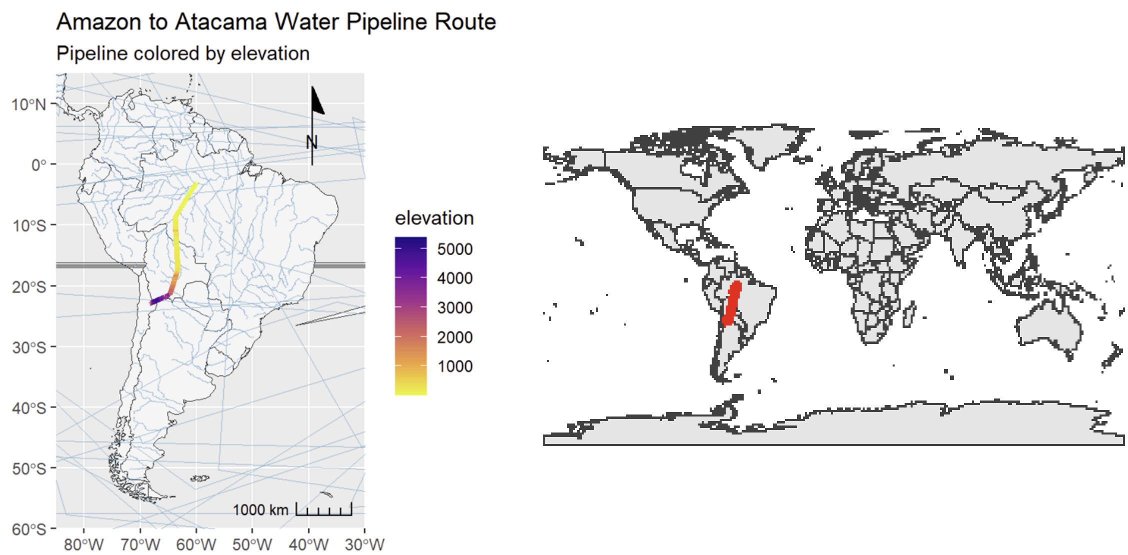
Graphical Abstract



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/m³) /
g : Gravitational acceleration (9.81 m/s²)

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.

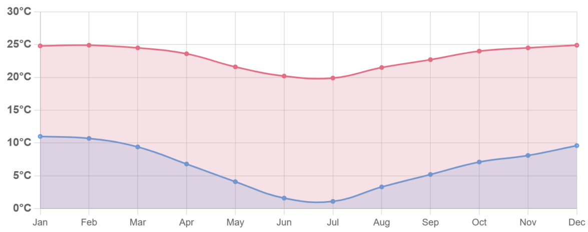


Figure 1. Atacama Desert Weather & Climate [5]

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·cm³/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 ΔT≤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	~ 10%
	USD	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.

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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)
```

```r
# 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,
```

```r
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() +
```

```
  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
```

```
    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)
```