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

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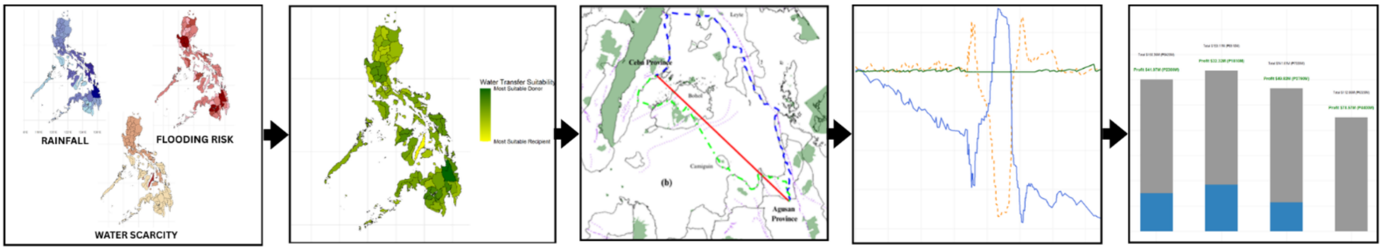
Graphical Abstract



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

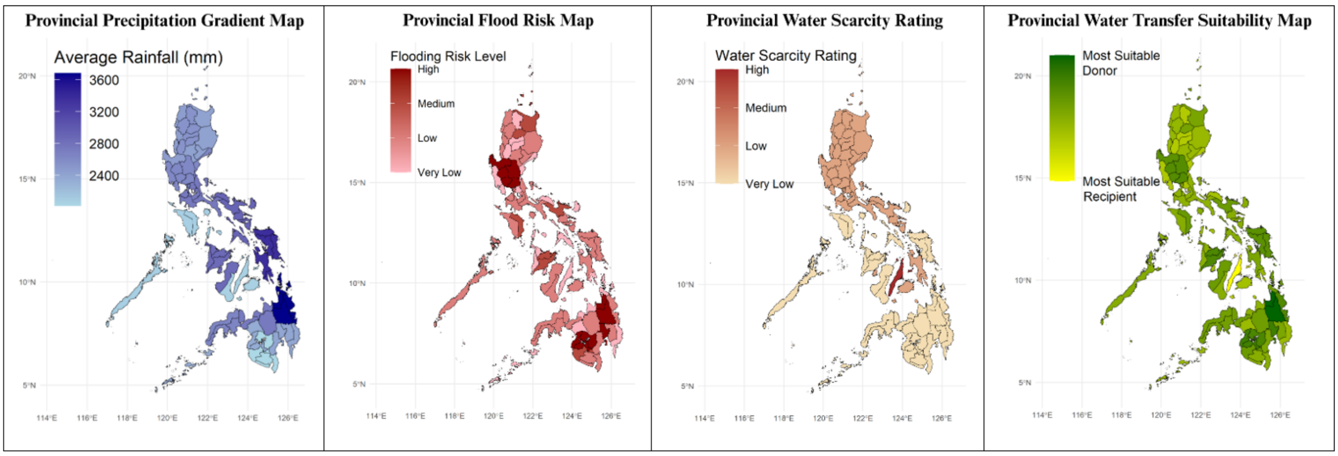


Figure 1. Heat maps for (from left to right): (a) annual precipitation, (b) flooding risk level, (c) water scarcity rating, and (d) overall water transfer suitability in the Philippines.

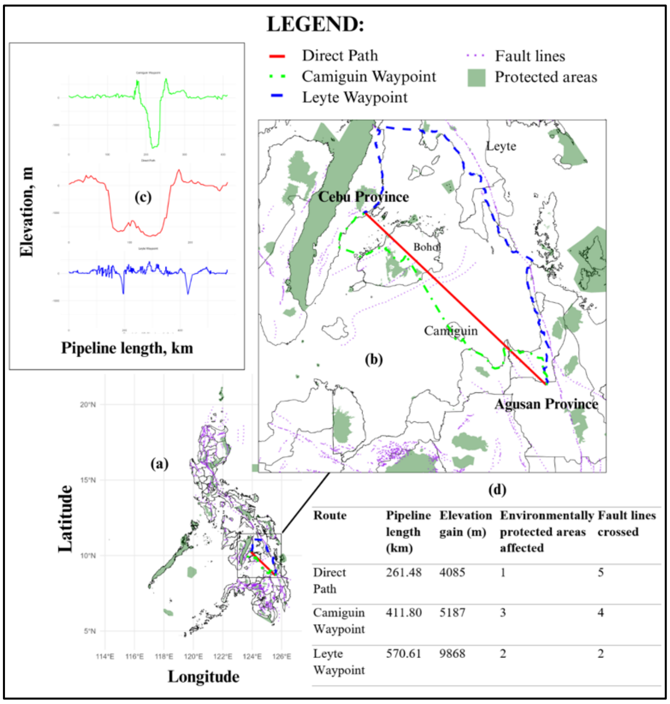
Visayas, particularly Cebu, experiences water scarcity, intensified by urbanization and high-water demand, with Metro Cebu classified as a water-critical area.[26]

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.



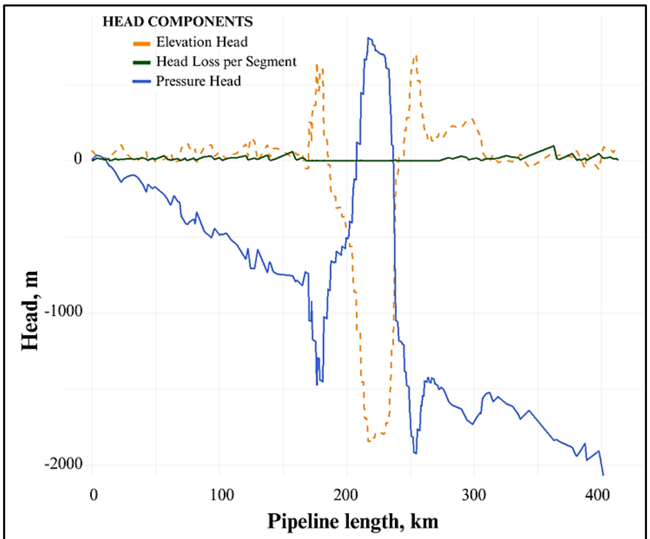
Route	Pipeline length (km)	Elevation gain (m)	Environmentally protected areas affected	Fault lines crossed
Direct Path	261.48	4085	1	5
Camiguin Waypoint	411.80	5187	3	4
Leyte Waypoint	570.61	9868	2	2

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]

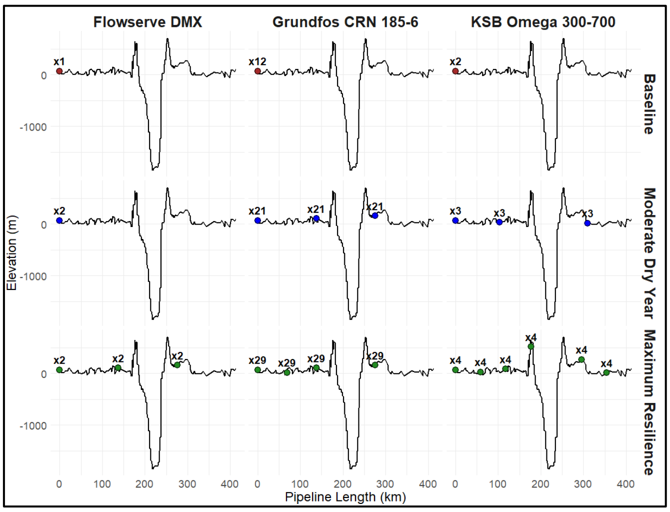


Figure 4. Elevation profiles of pipeline showing optimized pump station layouts (in dots) for three pump models for different scenarios.

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].

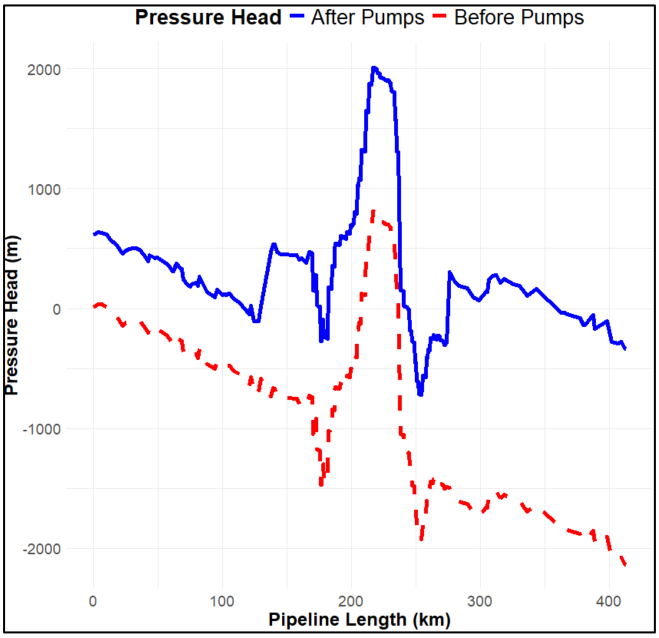


Figure 5. Pressure head profile along the pipeline before and after pump installation.

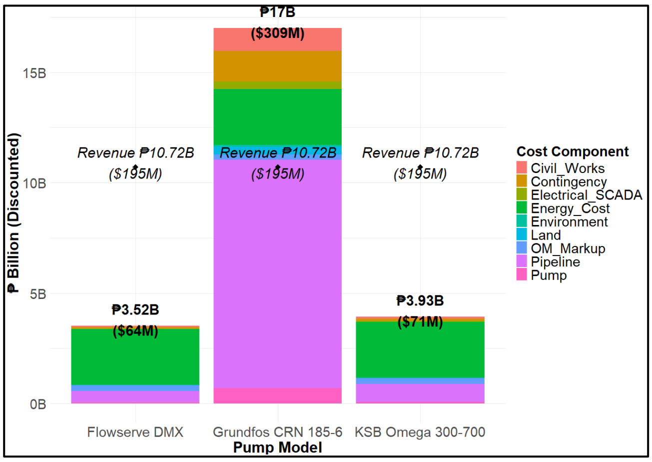


Figure 6. Lifecycle cost breakdown and revenue comparison for three pump models.

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.

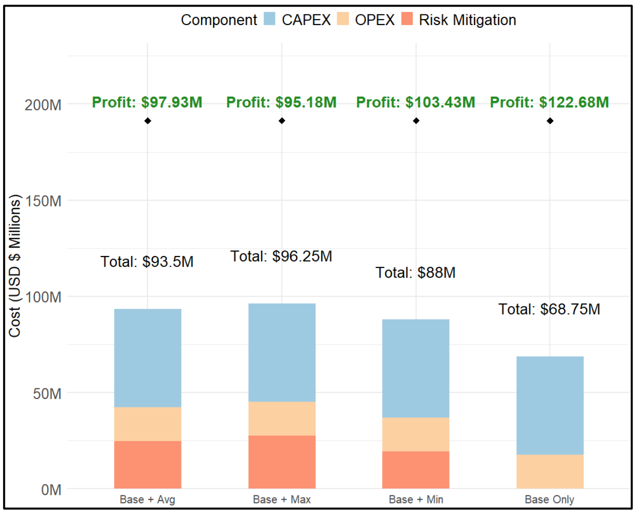


Figure 7. Lifecycle cost breakdown and profit under different risk scenarios for Flowserve DMX in USD.

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 km², 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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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
# -----------------------------
```

```
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)
  )
```