Tarrodan National Insurance Program for Earthen Dams

SOA Student Research Case Study Challenge 2025

INTERSTELLAR

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1. Objectives

1.1. Executive Summary

Recent global disasters from earthen dam failures have highlighted the risks faced by communities in Tarrodan, prompting legislative action. To protect residents and ensure economic resilience, the newly established Earthen Dam Commission is developing a national insurance program that balances affordability, sustainability, and stakeholder interests.

This report presents the proposal for the federal government's mandatory dam insurance program, which seeks to improve dam safety through risk-based premiums, comprehensive coverage, and climate adaptation measures. The program will cover 6,552 highly and significantly hazardous dams, with the government assuming responsibility for 80% of losses in the event of smaller incidents and utilising catastrophe bonds for larger-scale failures. In addition to insurance coverage, the program includes non-insurance features such as subsidies for dam assessment, mandatory spillway control, and a public education initiative. Climate adaptation strategies, including IoT-based monitoring and AI-driven predictive analytics, will enhance dam resilience and ensure long-term safety.

The proposed program is expected to significantly reduce the financial impact of potential dam failures, while establishing a sustainable funding mechanism for the repair and rehabilitation of affected dams. With an overall projected outcome reflected in a net present value (NPV) of 251.44 Qm, the program aims to break even.

Key risks include technological challenges, climate uncertainty, and participation risks. Strategies for mitigating these risks involve improving public engagement and enhancing predictive models.

1.2. Main Objectives & Key Metrics

The national dam insurance program aims to achieve the following objectives:

i. Reduce dam owners' financial risk, as they no longer bear the entire cost of losses following a failure.
ii. Faster restoration for communities relying heavily on dams for their daily activities.
iii. Incentivise infrastructure improvement (e.g. controlled spillway) to reduce dam failure risks.
iv. Improve dam regulation, clarify ownership and liability responsibilities.
v. Improve public engagement and raise awareness of dam failure risks, reducing third party losses in case of failure.

For the first 5 years of the program, key metrics for monitoring the program's success include:
i. Claims Frequency and Severity: to assess the effectiveness of risk-based premiums
ii. Risk Exposure of Covered Dams: to ensure premiums align with actual risks
iii. Inspection and Compliance Rates: to track adherence to preventive measures
iv. Spillway Control Implementation: to evaluate risk mitigation efforts, and
v. Public Engagement Metrics: to measure the effectiveness of education and outreach.

These will be reported annually, with claims and risk exposure tracked quarterly or semi-annually for timely adjustments.

2. Program Design

2.1. Insurance Features

2.1.1. Risk-based Premiums

The premium structure for the program is risk-based, as we currently lack claims data to accurately price premiums based on historical losses. Instead, premiums are determined by assessing the risk exposure of each dam. To ensure transparency, we utilise a Generalised Linear Model (GLM), which takes into account various risk factors such as the age, location, and condition of the dam (controlled spillway, inspection frequency etc). The use of GLM ensures that the pricing is consistent, objective, and based on quantifiable risk parameters, making the process equitable and transparent.

2.1.2. Coverage Scope

All highly hazardous and significantly hazardous dams (6,552 dams) will be required to participate in the program. If the risk exposure is below the annually determined catastrophe bond threshold, the government will cover 80% of Dam Repair and Third-Party Losses in the event of failure, as these dams pose a direct threat to public safety and the financial risk is too high for policyholders to handle on their own. Dam owners will be responsible for paying the remaining 20% of losses. Any losses exceeding the threshold will be covered by the catastrophe bond. In terms of premium contributions, dam owners will pay 80% of the total risk exposure through premiums.

The owners of the remaining dams will be responsible for their own insurance coverage, maintenance costs, and ensuring compliance with national dam safety regulations.

2.2. Non-Insurance Features

2.2.1. Preventive Measures

Prior to the commencement of the program, we will give out subsidies for the inspection of dams which meet one or more of the following criteria:

i. Haven’t been assessed for more than 5 years
ii. No information on Assessment Date (missing values)
iii. No information on Assessment Rating (missing values)

This would also help us in terms of getting a better understanding of the dam’s current hazard level and conditions. Overall, around 2/3 of dams (4382 dams) in the program qualify for this grant.

All dams are required to have spillway control measures by the end of a five-year period. Spillway control involves the use of adjustable structures such as crest gates to regulate water flow and maintain reservoir levels below critical thresholds (US Army Corps of Engineers, 2000). This helps prevent sudden surges, reduce overflow risks, and improve overall flood regulation. According to our model, the risk of third-party losses is reduced by 14% if the spillway is controlled, holding other variables constant.

Range of Size (m3)	Amount	Number of dams qualified	Total
0 – 1.5 million	Q1,000	2208	Q2,208,000
1.5 – 10 million	Q5,000	1319	Q6,595,000
>10 million	Q10,000	855	Q8,550,000

2.2.2. Public Engagement

To enhance public awareness and technical knowledge of dam safety, our proposed Dam Safety Education Program (DSEP) incorporates key elements from established national training initiatives, such as the Federal Emergency Management Agency (FEMA)'s dam safety training courses.

The DSEP is structured around three primary objectives: risk awareness, emergency preparedness, and technical capacity building. In recognition of the diverse roles and responsibilities across the dam safety landscape, the DSEP offers tiered training modules tailored to different stakeholder groups, including dam owners, engineers, emergency response personnel, local government officials, and the public. It employs a multi-model learning framework, incorporating instructor-led training, online self-paced courses, community workshops, and hands-on exercises (Mehta et al., 2020).

Stakeholder Group	Training Focus
Dam Owners / Operators	Routine inspection, maintenance best practices, hazard mitigation
Engineers / Technical Staff	Seepage monitoring, structural risk assessment, hydraulic modelling
Emergency Responders	Virtual Table-Top Exercises (VTTX), crisis management, coordination
Local Officials/Community Members	Public awareness campaigns, digital resources, signage programs, safety drills

2.2.3. Climate Adaptation

Recognising the escalating climate risks to earthen dams, the proposed national insurance program for Tarrodan integrates targeted adaptation measures to enhance structural resilience and risk mitigation. Traditional risk assessments, which assume stationary climatic conditions, fail to account for shifting hydrological patterns, increasing extreme rainfall, and prolonged drought-induced soil instability, necessitating a dynamic, data-driven safety framework (Fluixá-Sanmartín et al., 2018).

This proposal advocates for IoT-based Structural Health Monitoring (SHM) systems, enabling continuous tracking of seepage, soil moisture, and structural deformations, providing real-time insights to support pre-emptive maintenance and failure prevention (Khan et al., 2024). Coupled with AI-driven predictive analytics, which refine hazard classification through advanced modelling of historical and climate data, these technologies will facilitate targeted intervention, optimised resource allocation, and long-term infrastructure sustainability (Assaad & El-adaway, 2020).

By embedding these technologies into dam governance, the program shifts from reactive crisis management to proactive climate adaptation, strengthening safety and informing forward-looking policy decisions for infrastructure planning under climate uncertainty.

2.3. Timeline and Evaluation

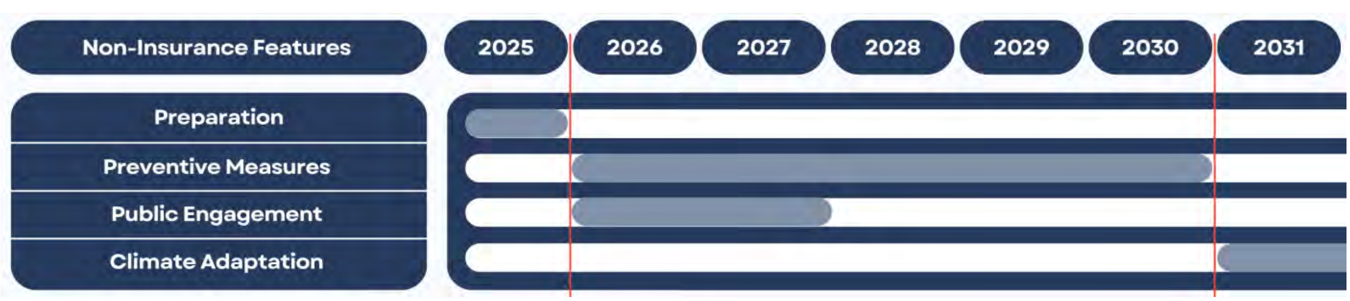


Figure 1: Program timeline

The timeline for the program is outlined above. In terms of pricing, the premiums for the first five years will be calculated based on risk exposures. As claims data begin to accumulate, we will adopt a hybrid pricing approach, combining both risk exposure-based and experience-based methods. Over time, we will gradually transition to a fully claims-driven pricing model.

Since the premiums are risk-based, dam owners are incentivised to improve the condition of their dams, as these improvements will be directly reflected in lower premiums. Furthermore, the risk loadings are based on the specific characteristics of the regions, which incentivises whole regions to take collective action in reducing risk. After 5 years, dams that pose an unacceptably high level of risk will be considered for decommissioning to mitigate further financial exposure.

3. Financial Results

3.1. Overall Result

Over the next five years, the primary cash inflow—contributing more than 50%—will come from pure premium. In the first year, we will also receive a significant one-time cash inflow from issuing catastrophe bonds, transferring extreme risk to the market. Additional revenue streams include expense loadings, region-specific risk loadings, and 30% contingency loadings. Given its risk-based nature, the loading is needed during this period to ensure financial viability but will be reassessed in the long run to reflect actual claim payments.

We will incur an upfront cost of 18.7 Qm, allocated to assessment grants and the educational program. The largest expense category is claim payments, based on the average of our simulated claims. Other key expenses include operational and maintenance costs, as well as staff salaries.

The financial summary is provided below, with an overall near break-even outcome, reflected in an NPV of 251.44 Qm.

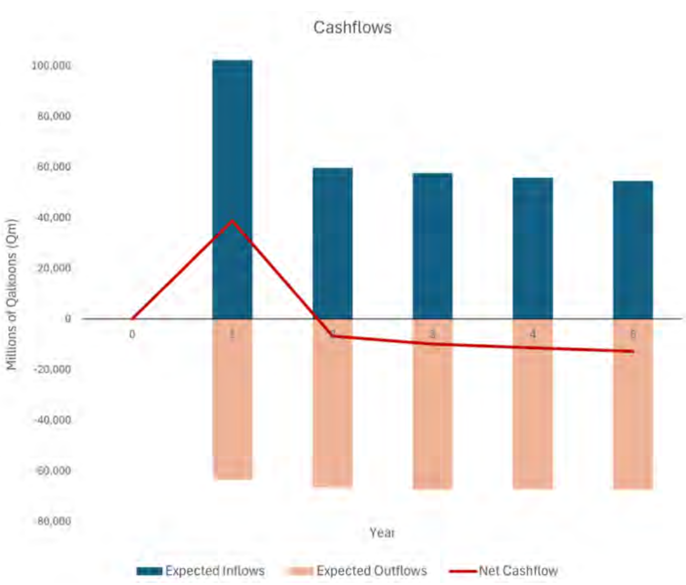


Figure 2: Expected Inflows, Outflows and Net Cashflows over the next five years

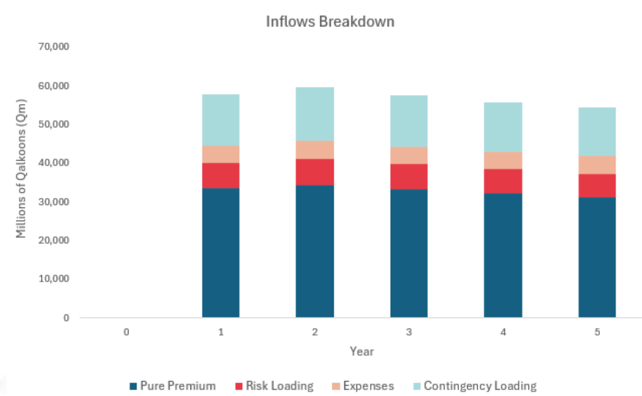


Figure 3: Breakdown of expected inflows

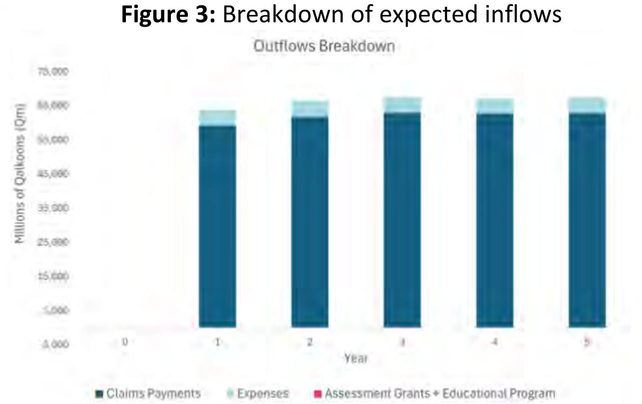


Figure 4: Breakdown of expected outflows

3.2. Program Sustainability

With Tarrodan's nominal GDP reaching 8 trillion Qalkoons in 2023, the program's total cash inflows and outflows are negligible and unlikely to disrupt the broader economy. The risk variations are directly incorporated into our pure premium calculations and revenue projections as they are purely risk-based.

Regional cost variations are notable. On average, Lyndrassian dams incur 26% lower repair costs than Flumevale but spend 45% more on third-party liabilities. In contrast, Navaldia's repair costs are 8% higher than Flumevale's, yet third-party expenses are 82% lower, likely due to Flumevale's higher population density. These differences account for regional factors such as population distribution and housing costs.

Frequent inspections reduce repair costs by 9.3% per year but do not affect third-party liabilities. Dam age increases repair costs by 0.27% and third-party liabilities by 0.43% annually. These findings highlight the cost-saving potential of regular inspections and the growing liability risks associated with aging infrastructure.

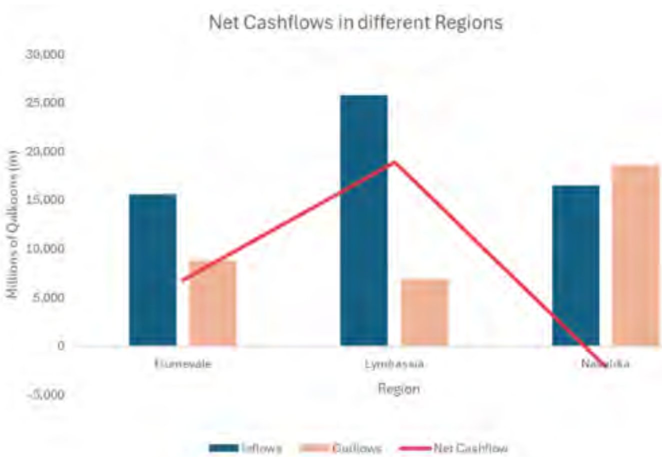


Figure 5: Net Cashflows by Region

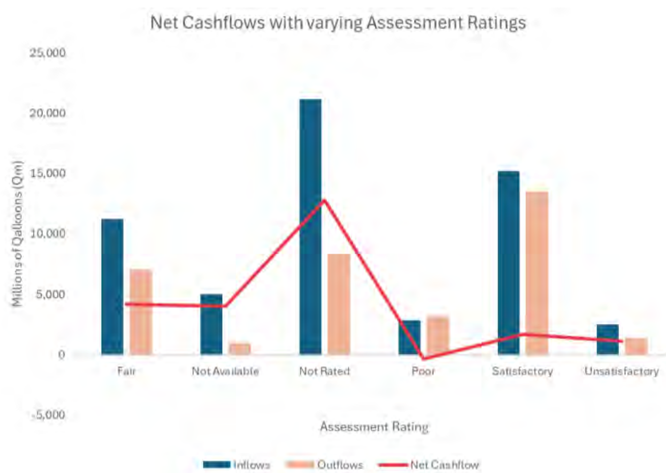
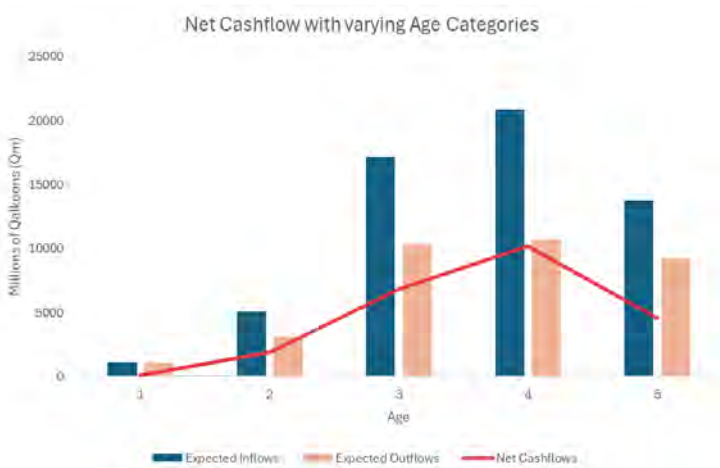


Figure 6: Net Cashflows by Assessment Ratings



Age Category	Age
1	<20
2	<40
3	<60
4	<80
5	>=80

Figure 7: Net Cashflows by Age Categories

Figure 5 compares inflows and outflows for each region highlight the relationship between the premiums charged and the simulated claims payment. Despite premiums being set high in Flumevale and Lyndrassia to account for potential risks, not many simulated failures occurred, suggesting that the actual risk of failure in these regions was lower than anticipated. On the other hand, in Navaldia, the premiums charged are closer to the simulated losses, which reflects a more accurate alignment of the pricing with the actual risk exposure in this region.

This disparity arises because pricing is designed to balance risk across a large sample of events. Although individual outcomes may vary, the model adjusts for regional risk profiles. As a result, premiums reflect potential risks that could materialise under different scenarios. This is particularly relevant for third-party liability, where dams in Lyndrassia face the highest exposure. In terms of Loss Given Failure (LGF) liability, Lyndrassia ranks highest, followed by Navaldia and Flumevale, justifying the region's higher premiums.

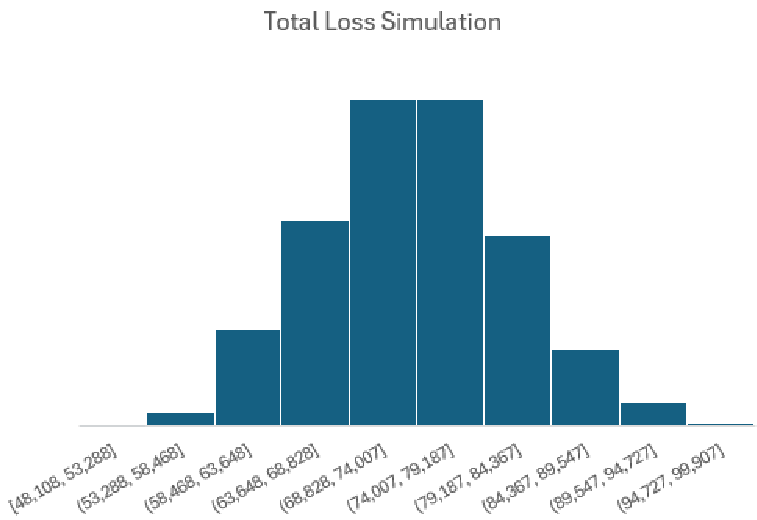


Figure 8: Total Loss Simulation for Year 1

Similar to the National Flood Insurance Program (NFIP), our approach does not price policies to fully cover catastrophic loss years using premiums alone. Instead, in extreme cases, additional financial support may be required, similar to how the NFIP relies on Treasury borrowing to meet obligations (Kousky & Shabman, 2014).

Each year, we will determine a separate catastrophe bond trigger point. In Year 1, there is a 5% probability of losses exceeding 84.4 billion Qalkoons. As a result, the trigger point is set at this threshold, meaning that if total losses surpass 84.4 billion Qalkoons, we will retain the principal from the catastrophe bond to cover the excess losses.

Additionally, like the NFIP, our program must incorporate premium adjustments and discounts to balance affordability and risk. Consequently, risk loadings may need to be adjusted based on participation rates and public perception to ensure sustainability.

3.3. Scenarios Analysis

Our scenario analysis provides a comprehensive view of potential financial outcomes by examining best-case, worst-case, and base-case scenarios. The best-case and worst-case scenarios represent the extremes: the worst-case scenario is based on the highest loss observed in 1,000 simulations, while the best-case scenario reflects the lowest claims payment the insurer needs to pay out.

To maintain consistency, inflows remain constant across all scenarios, while only claims payments vary.

Year	Worst case	Best case	Base case
0	(18.77)	(18.77)	(18.77)
1	29,767.17	58,253.08	37,933.49
2	(15,223.96)	10,515.49	(6,523.20)
3	(17,857.55)	8,986.45	(9,233.21)
4	(19,466.95)	8,317.77	(10,409.37)
5	(21,245.50)	4,011.83	(11,497.51)
NPV	(44,045.57)	90,065.84	251.44

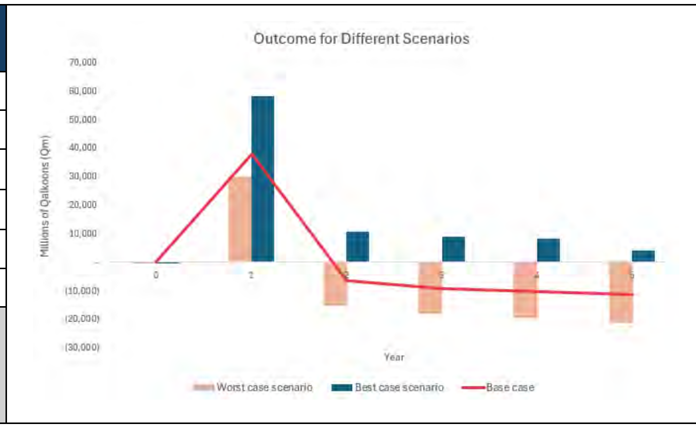


Figure 9: Scenario Analysis and Cashflows under different scenarios

- Worst-case scenario: A significant claims payout leads to a negative net cash flow of 44 billion Qalkoons.
- Best-case scenario: Minimal claims result in a positive cash flow of 90 billion Qalkoons.
- Base-case scenario: The mean total loss from 1,000 dam failure simulations yields a net cash flow of 251.44 Qm, providing a balanced estimate of expected conditions.

While this profit is expected to be moderate, it plays a crucial role in strengthening the insurance program's financial stability. Simulations indicate that a budget surplus is unlikely, but if one occurs within the first five years, it will be redistributed to policyholders whose dams remain intact during this period.

4. Assumptions

Metric	Assumed Value	Rationale
Inflation Rate	2.48%	After differencing the inflation rate once, the series is white noise. Thus, this is a naïve forecast for the next 5 years. Given that the rate decreased quickly after Covid, this is a reasonable estimate.
Third Party Losses Reduction Rate	7% for Year 3 and 7.5% for Year 4 and 5 as a result of better public engagement	Based on the outcome of Community Fireguard Program (Vic, Australia). We adjusted the number according to dam failure characteristics. The first 2 years are dedicated to the implementation of the program, and we assume the results will materialise from Year 3.
Spillway Control Rate	100% control rate by the end of Year 5, assuming an S curve adoption rate	It is a requirement to install the gate at the end of Year 5. We would assume that the adoption is slow at first, speeding up in the middle years and then slow down again.
Risk Loadings	Flumevale: 30% Lyndrassia: 20% Navaldia: 10%	This assessment is based on regional disaster risks. Floods are the most frequent cause of dam failures, followed by earthquakes and tsunamis (Statista, 2025). The NFIP's Risk Rating 2.0 applies up to 0.1% geographic risk loading per property, but since dam failures impact entire communities, we set regional loadings between 10% and 30%.

Assessment Grant	Q17,353,000	Multiply the total number of dams qualified and the grant amount at each tier and then sum them up.
Public Engagement Program	Q1,000,000	Cost of Public Engagement Program is calculated based on the National Dam Safety Program (NDSP) (US).
Expenses	Administration Costs: 11 % of pure premium. + Operational costs: 5% + Staffing & HR: 3% + Regulatory & Compliance: 1% + Technology & Infrastructure Maintenance: 2%	The administrative costs are derived from the expense structure of the NFIP's Write-Your-Own (WYO) program, as detailed in the Affordability of National Flood Insurance Program Premiums: Report 1 (National Academies of Sciences, Engineering, and Medicine, 2015). The NFIP allocates 12.5% - 13.5% of written premiums to company expenses, which include operational costs, staffing, compliance, and technology expenses. Additionally, FEMA's analysis accounts for costs associated with claims processing and regulatory compliance. Our cost allocation is expressed as a % of pure premium following the framework.

For more details of calculations, see Appendix 8.4.

5. Risks and Risk Mitigation

5.1. Risk Matrix

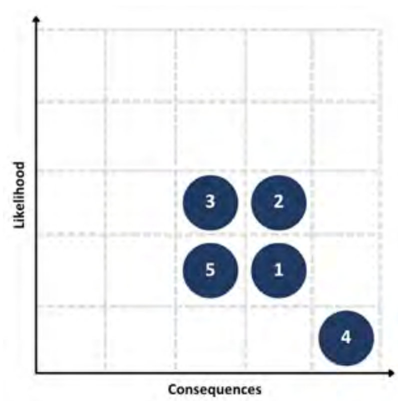


Figure 10: Risk Assessment Matrix

Based on the risk matrix, most main risks have a low likelihood of occurring but could result in moderate to high consequences for the program's performance.

To mitigate these risks, appropriate measures will be implemented to minimise their effects and ensure the program's successful execution.

5.2. Main Risks & Mitigation

Risk	Description	Mitigation Strategy
1 Pricing Risk	Uncertainties in forecasting potential losses due to factors like inaccurate data, data imputation methods, model limitations, and changes in underlying	Monitor cash flows to ensure expenses and income are in line with expectation. Monitor trends and events closely to adjust underlying

	conditions. Assumptions made during model development can affect outcomes, and reliance on historical data may not fully capture future trends or extreme events.	assumptions and reflect that into the premium price every year.
2 Environmental Risk	Natural and human-induced environmental changes that may affect dam safety and increase the potential for financial losses, including extreme weather events, seismic activity, altered rainfall patterns, and changes in land use or soil conditions. Such factors can place stress on dam infrastructure, compromising its integrity.	In the short-term, we will enhance emergency water releases, conduct real-time monitoring and inspections, and use temporary reinforcements to prevent damage. In the long-term, we can apply AI analytics and infrastructure improvements specific to disasters in each region. Details of such improvements can be found in Appendix 8.5.
3 Stakeholder Risk	Potential resistance or non-compliance from key stakeholders, including dam owners, operators, and the public due to concerns over costs, time commitments, or perceived disruptions. Public perception issues, such as scepticism and lack of trust, can hinder participation and compliance.	Subsidies and grants for dam owners to encourage compliance. The NFIP shows that a major challenge in risk mitigation is people's lack of awareness of their exposure to hazards (Thomas & Leichenko, 2011). Hence, it is important to communicate clearly the effectiveness of the program and address any concerns for citizens.
4 Catastrophic Loss Risk	Large-scale event, such as a major dam failure, could result in claims far exceeding initial projections.	Catastrophe bonds will be triggered when losses exceed the threshold. Even though a national program, e.g. NFIP, is not priced to cover extreme loss year (Kousky & Shabman, 2014), we incorporated a profit margin to ensure we have a reserve fund for catastrophic events.
5 Technology Risk	Technology risk in dam safety encompasses automation failures. Reliance on Supervisory Control and Data Acquisition (SCADA) systems, sensors, and automated floodgates introduces failure risks from software glitches, hardware malfunctions, or operational errors, potentially compromising flood management.	Adopts AI and IoT-driven monitoring to enhance dam resilience and mitigate technology risks (Khan et al., 2024). By integrating satellite imagery, geospatial analytics, and sensor networks, this approach enables real-time anomaly detection, improving predictive maintenance and structural integrity assessments. It minimises monitoring blind spots, enhances early warning capabilities, and supports proactive risk management.

6. Data and Data Limitations

6.1. Data Sources

Data Source	Description
Tarrodan's data	Dam dataset, encyclopedia entry, and economic data provided.
Natural Disaster Programs such as NFIP (US), CFP (Australia); reports and academic journals	Various Costs and Rates used in our calculation of financial results.

6.2. Data Limitations

Limitation	Explanation	Effects
Missing Values	The dataset contained missing values across different variables. To ensure completeness, we used the mice package in R for imputation: • Categorical Variables: Imputed using Bayesian Polytomous Regression to maintain distribution integrity. • Numerical Variables: Imputed using predictive mean imputation to reduce the impact of extreme values.	Bayesian imputation assumes a multinomial distribution, which may not perfectly reflect the real-world data distribution, potentially introducing bias.
Data definition	Data definitions were not clear in the dam dataset.	We used our best judgements and research to determine the definitions.

7. Conclusion

In conclusion, the proposed mandatory dam insurance program offers a comprehensive and proactive approach to improving dam safety and mitigating risks. By combining risk-based premiums, targeted climate adaptation measures, and preventive strategies, the program aims to enhance the resilience of hazardous dams while ensuring financial sustainability. With a focus on rigorous monitoring, public engagement, and the use of advanced technologies, the program is positioned to effectively reduce the potential financial burden of dam failures.

8. Appendix

8.1. Data Cleaning & Exploratory Data Analysis

Data Quality Check:

Feature Name	Values / Structure	Quality Check
ID	SOA12345	The data is actually in the form SOAD12345. No duplicates found
Region	Flumevale, Lyndrassia, Navaldia	CLEAN
Regulated Dam	Yes, No	CLEAN
Primary Purpose	12 types	1184 blanks
Primary Type	12 types	257 blanks
Height (m)	Numerical	There are 24 observations with height of 0
Length (km)	Numerical	There are 254 observations with length of 0 and 2671 blanks
Volume (m3)	Numerical	There are 3160 observations with volume of 0 and 9678 blanks
Year Completed	1748—2023	1384 blanks
Years Modified	Alphanumeric	18995 blanks
Surface (km2)	Numerical	There are 1870 observations with value of 0 and 2798 blanks
Drainage (km2)	Numerical	There are 5208 observations with value of 0 and 2798 blanks
Spillway	Uncontrolled, Controlled	12786 blanks
Last Inspection Date	DD-MM-YYYY	There are 1 observation with the year 2031 and 10024 blanks
Inspection Frequency	Numerical	There are 4459 observations with value of 0 and 8116 blanks
Distance to Nearest City (km)	Numerical	10229 blanks. Assuming 0s mean that the dams are inside the city.
Hazard	Low, High, Significant, Undetermined	CLEAN
Assessment	Not Rated, Satisfactory, Fair, Not Available, Poor, Unsatisfactory	2537 blanks
Assessment Date	DD-MM-YYYY	9773 blanks
Probability of Failure	Numerical	CLEAN
Loss given failure – prop (Qm)	Numerical	7 blanks
Loss given failure – liab (Qm)	Numerical	12 blanks
Loss given failure – BI (Qm)	Numerical	10730 blanks

New Variables:

New Variables	Calculation	Rationale
Age	2025 – Year Completed	Easier to work with than year.
Size (km3)	Height (km) * Surface (km2)	This is a proxy for size. It is used instead of volume because there are too many missing values for volume.
Years from Last Inspection	2025 – Year (Last Inspection Date)	A proxy for the level of inspection and maintenance of dams.
Annual Probability of Failure	(Probability of Failure + 1)^(1/10) – 1	Assuming the probability of failure is constant across the 10-year period. Geometric mean is used because the risk is often compounding instead of adding up.

Key findings:

- Most dams are located in Navaldia and Lyndrassia (80%).
- Flumevale excels in dam regulation, while Lyndrassia performs the worst. The same pattern holds for inspection frequency, with Flumevale leading. Additionally, Flumevale has the most complete reporting statistics, whereas Navaldia has the highest number of missing values.
- Hazards are high near cities and low farther away.
- Regarding the size, 'High' hazard dams are 10 times bigger than 'Significant', and more than 100 times bigger than 'Low'. 'Undetermined' dams are very small.
- Probability of failure are not that different for regions. It costs the most to repair dams in Flumevale, but that makes sense because the size of the dams is significantly bigger there (average of 0.2km3) compared to the other 2 regions (average of 0.08km3).
- Non-regulated dams are located nearer to the cities.
- Most of the spillways are uncontrolled.

8.2. Data Imputation

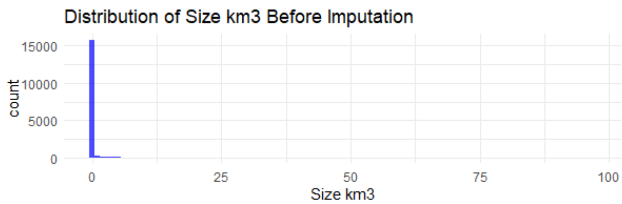
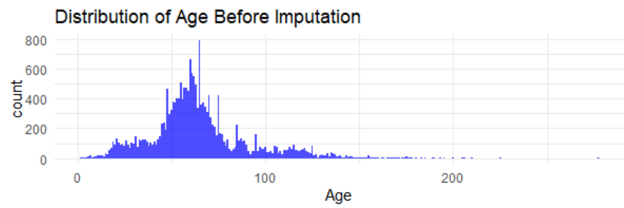
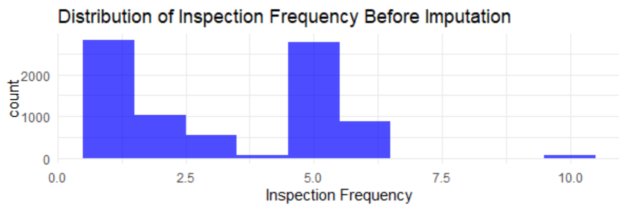
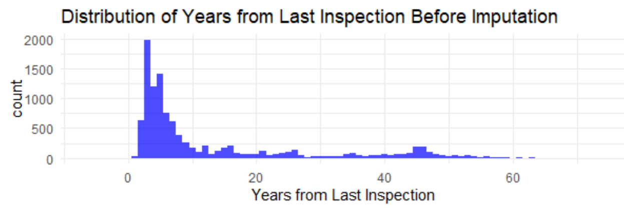
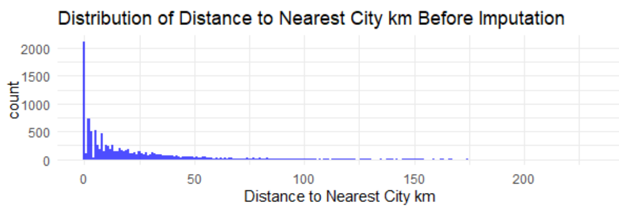
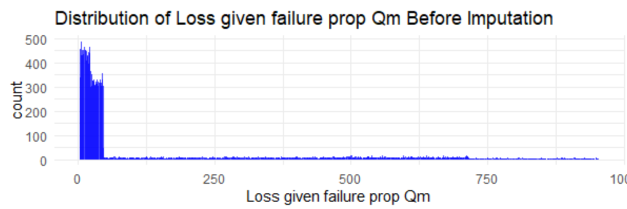
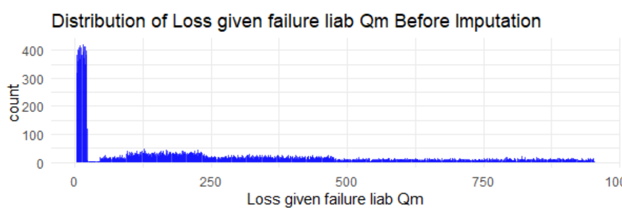
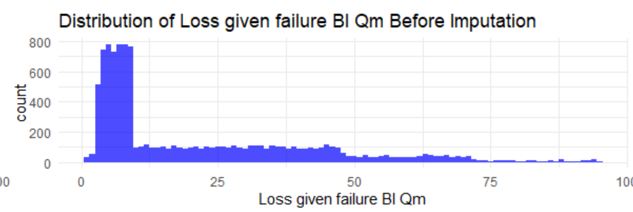
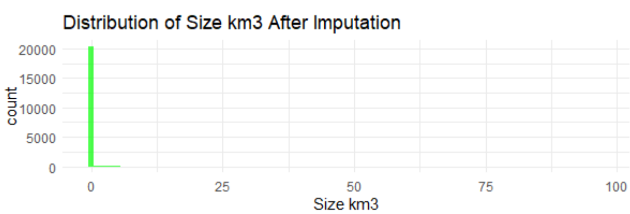
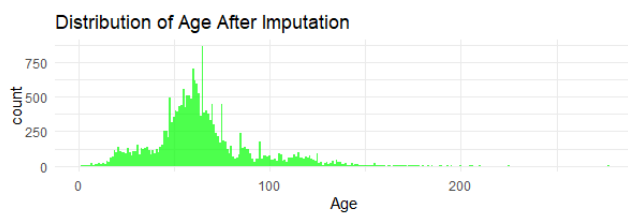
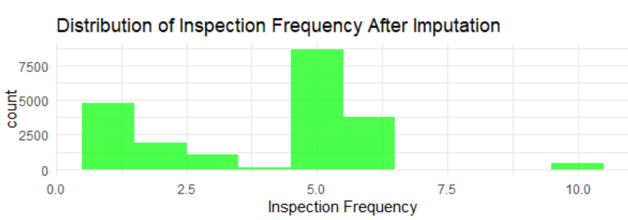
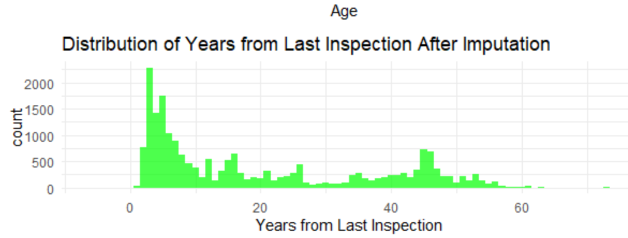
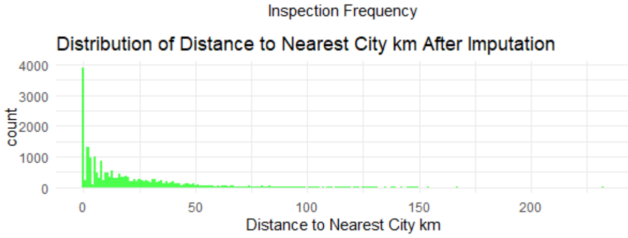
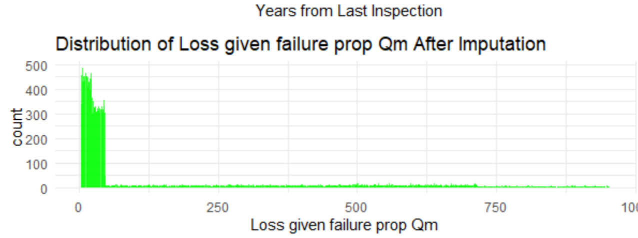
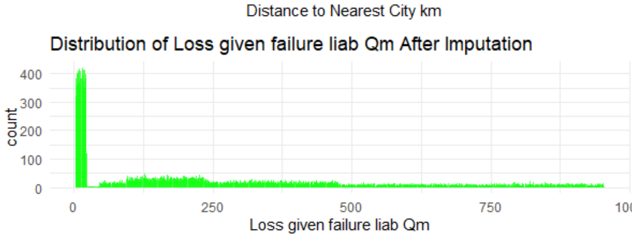
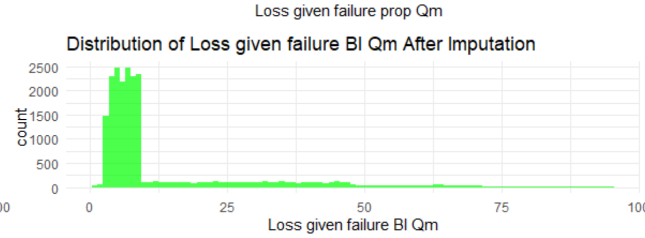
Missing data poses a significant challenge in data analysis, particularly in building pricing models, where data completeness and accuracy directly influence model performance. The choice of imputation method is crucial to preserving the statistical properties of the dataset and minimising distortions that could lead to biased predictions. For this project, we implemented Predictive Mean Matching (PMM) for continuous variables and Bayesian Polytomous Regression (BPR) for categorical variables, as these approaches provide a more robust and flexible way to handle missing data while maintaining key relationships essential for downstream modelling.

Predictive Mean Matching (PMM) was selected for continuous variables because it retains realistic values from observed data rather than imputing an arbitrary mean, which could reduce variance and distort the original distribution. Given that some of our continuous variables exhibit skewness, PMM is particularly beneficial as it preserves the existing distribution shape by drawing imputed values from actual observations rather than generating artificial values. This is critical for the pure premium pricing model, where the distribution of key variables - such as age and size - affects the accuracy of predictions. By ensuring that imputed values reflect the original data's characteristics, PMM helps maintain the validity of statistical inferences and reduces the risk of biased model outputs.

For categorical variables, Bayesian Polytomous Regression (BPR) was chosen to address the limitations of traditional mode imputation, which assigns missing values to the most frequent category without considering underlying dependencies. This can lead to extreme class imbalances and distort variable relationships, negatively impacting predictive models. BPR, on the other hand, probabilistically estimates missing values by leveraging existing data structure and accounting for uncertainty. This ensures that categorical variables retain their natural distribution, reducing the risk of artificially inflating certain categories. In pure premium model, where categorical factors such as the hazard level and assessment rating play a crucial role, preserving these relationships is essential for accurate risk assessment and premium calculations.

Both methods rely on key statistical assumptions that align well with our dataset. PMM assumes a Missing at Random (MAR) mechanism, meaning that the probability of missingness depends on observed variables rather than unobserved factors. This assumption is reasonable given the structure of our data, where missing values are more likely to occur due to reporting inconsistencies rather than systematic biases. BPR assumes a multinomial distribution for categorical variables, making it well-suited for our data, which includes categorical predictors with multiple levels.

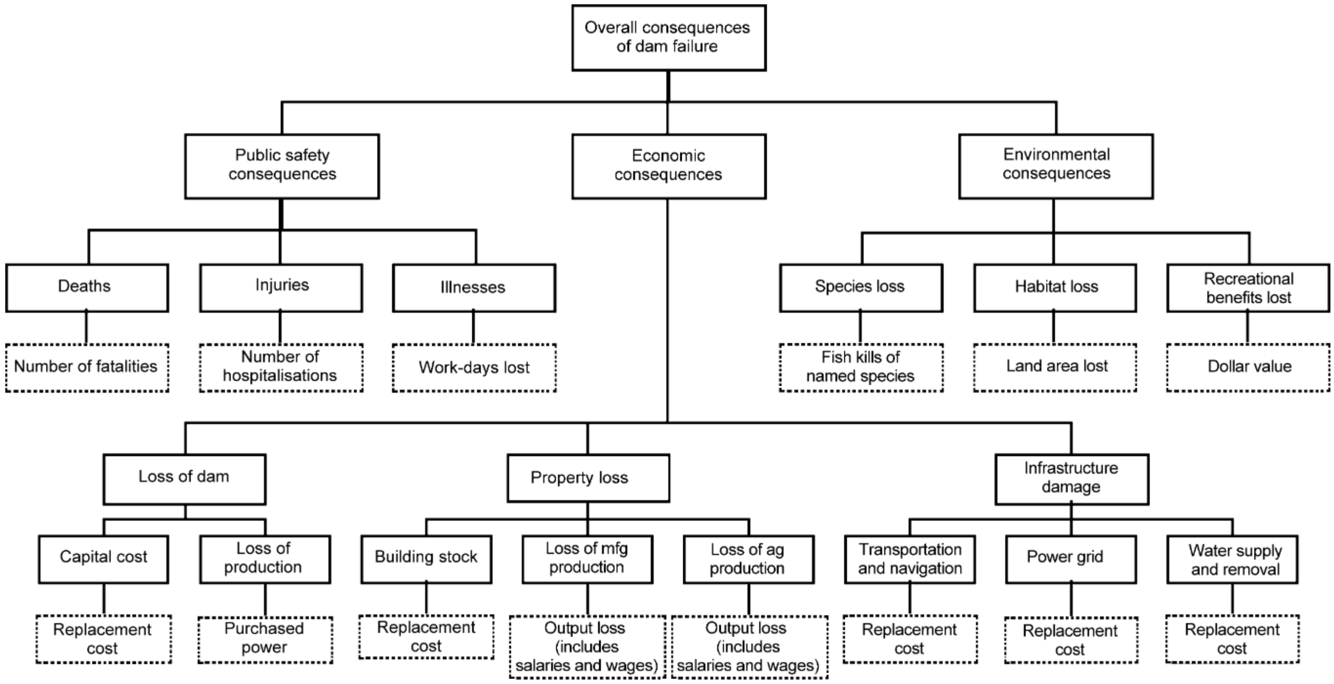
To evaluate the impact of these methods, we compared the distributions and summary statistics before and after imputation. Each method offers distinct advantages that directly benefit pricing model development; yet they also come with computational costs. Despite these challenges, the benefits of maintaining data integrity far outweigh the costs, as cleaner and more representative data lead to more reliable pricing models.


Distribution of Size km3 Before Imputation
count
Size km3

Distribution of Age Before Imputation
count
Age

Distribution of Inspection Frequency Before Imputation
count
Inspection Frequency

Distribution of Years from Last Inspection Before Imputation
count
Years from Last Inspection

Distribution of Distance to Nearest City km Before Imputation
count
Distance to Nearest City km

Distribution of Loss given failure prop Qm Before Imputation
count
Loss given failure prop Qm

Distribution of Loss given failure liab Qm Before Imputation
count
Loss given failure liab Qm

Distribution of Loss given failure BI Qm Before Imputation
count
Loss given failure BI Qm

Distribution of Size km3 After Imputation
count
Size km3

Distribution of Age After Imputation
count
Age

Distribution of Inspection Frequency After Imputation
count
Inspection Frequency

Distribution of Years from Last Inspection After Imputation
count
Years from Last Inspection

Distribution of Distance to Nearest City km After Imputation
count
Distance to Nearest City km

Distribution of Loss given failure prop Qm After Imputation
count
Loss given failure prop Qm

Distribution of Loss given failure liab Qm After Imputation
count
Loss given failure liab Qm

Distribution of Loss given failure BI Qm After Imputation
count
Loss given failure BI Qm

```
Summary statistics before imputation:
> print(summary(tarrodan_damdata))
        Region      Regulated Dam                                   Primary Purpose     Primary Type       Size km3            Age
 Flumevale :3522   No : 8754      Recreation                                :4469   Earth    :19368   Min.   : 0.000   Min.   :  2.00
 Lyndrassia:8406   Yes:12052      Flood Risk Reduction                      :4141   Gravity :  393   1st Qu.: 0.000   1st Qu.: 51.00
 Navaldia  :8878                  Fire Protection, Stock, Or Small Fish Pond:2964   Concrete:  259   Median : 0.001   Median : 61.00
                                  Irrigation                                :2941   Rockfill:  221   Mean   : 0.113   Mean   : 64.39
                                  Water Supply                              :2367   Other   :  106   3rd Qu.: 0.003   3rd Qu.: 73.00
                                  (Other)                                   :2740   (Other) :  202   Max.   :97.073   Max.   :277.00
                                  NA's                                      :1184   NA's    :  257   NA's   :4679     NA's   :1384
 Number of Modification         Spillway        Inspection Frequency Years from Last Inspection Distance to Nearest City km         Hazard
 Min.   :0.0000          Controlled  :  329   Min.   : 0.500       Min.   :-6.00              Min.   :  0.00                 High        : 5424
 1st Qu.:0.0000          Uncontrolled: 7691   1st Qu.: 1.000       1st Qu.: 4.00              1st Qu.:  1.63                 Low         :13645
 Median :0.0000          NA's        :12786   Median : 3.000       Median : 6.00              Median : 10.14                 Significant : 1724
 Mean   :0.1173                               Mean   : 3.232       Mean   :12.53              Mean   : 19.80                 Undetermined:   13
 3rd Qu.:0.0000                               3rd Qu.: 5.000       3rd Qu.:15.00              3rd Qu.: 27.98
 Max.   :7.0000                               Max.   :10.000       Max.   :73.00              Max.   :231.60
                                              NA's   :12575        NA's   :10024              NA's   :10229
          Assessment    Annual Probability of Failure Loss given failure prop Qm Loss given failure liab Qm Loss given failure BI Qm
 Fair           : 2088   Min.   :0.0002697            Min.   :  4.8             Min.   :  4.8             Min.   : 1.00
 Not Available :  504   1st Qu.:0.0073426            1st Qu.: 16.4             1st Qu.: 18.0             1st Qu.: 6.10
 Not Rated      :11580   Median :0.0089600            Median : 30.0             Median :167.6             Median : 9.30
 Poor           :  478   Mean   :0.0089927            Mean   :123.1             Mean   :253.7             Mean   :21.07
 Satisfactory   : 3279   3rd Qu.:0.0105635            3rd Qu.: 46.3             3rd Qu.:409.1             3rd Qu.:33.50
 Unsatisfactory:  340   Max.   :0.0181105            Max.   :952.7             Max.   :953.9             Max.   :95.40
 NA's           : 2537                                NA's   :7                 NA's   :12                NA's   :10730
Summary statistics after imputation:
> print(summary(tarrodan_damdata_imputed))
        Region      Regulated Dam                                   Primary Purpose     Primary Type       Size km3             Age
 Flumevale :3522   No : 8754      Recreation                                :4789   Earth    :19610   Min.   : 0.00001   Min.   :  2.0
 Lyndrassia:8406   Yes:12052      Flood Risk Reduction                      :4416   Gravity :  401   1st Qu.: 0.00045   1st Qu.: 51.0
 Navaldia  :8878                  Fire Protection, Stock, Or Small Fish Pond:3147   Concrete:  260   Median : 0.00093   Median : 61.0
                                  Irrigation                                :3090   Rockfill:  223   Mean   : 0.10819   Mean   : 64.4
                                  Water Supply                              :2472   Other   :  107   3rd Qu.: 0.00268   3rd Qu.: 73.0
                                  Other                                     : 979   Buttress:   73   Max.   :97.07317   Max.   :277.0
                                  (Other)                                   :1913   (Other) :  132
 Number of Modification         Spillway        Inspection Frequency Years from Last Inspection Distance to Nearest City km         Hazard
 Min.   :0.0000          Controlled  :  610   Min.   : 0.500       Min.   :-6.0               Min.   :  0.00                 High        : 5424
 1st Qu.:0.0000          Uncontrolled:20196   1st Qu.: 2.000       1st Qu.: 5.0               1st Qu.:  1.67                 Low         :13645
 Median :0.0000                               Median : 5.000       Median :13.0               Median : 11.70                 Significant : 1724
 Mean   :0.1173                               Mean   : 3.976       Mean   :19.8               Mean   : 20.57                 Undetermined:   13
 3rd Qu.:0.0000                               3rd Qu.: 5.000       3rd Qu.:36.0               3rd Qu.: 29.94
 Max.   :7.0000                               Max.   :10.000       Max.   :73.0               Max.   :231.60

          Assessment    Annual Probability of Failure Loss given failure prop Qm Loss given failure liab Qm Loss given failure BI Qm
 Fair           : 2545   Min.   :0.0002697            Min.   :  4.8             Min.   :  4.8             Min.   : 1.00
 Not Available :  625   1st Qu.:0.0073426            1st Qu.: 16.4             1st Qu.: 18.0             1st Qu.: 5.10
 Not Rated      :13121   Median :0.0089600            Median : 30.0             Median :167.8             Median : 7.30
 Poor           :  527   Mean   :0.0089927            Mean   :123.1             Mean   :253.8             Mean   :13.86
 Satisfactory   : 3586   3rd Qu.:0.0105635            3rd Qu.: 46.3             3rd Qu.:409.2             3rd Qu.: 9.50
 Unsatisfactory:  402   Max.   :0.0181105            Max.   :952.7             Max.   :953.9             Max.   :95.40
```

8.3. Program Design



Note. From "Risk and uncertainty in dam safety", by D. N. D. Hartford and G. B. Baecher, 2004, *Thomas Telford*, p. 256 (https://doi.org/10.1680/rauids.32705.0010). Copyright 2004 by Authors and Thomas Telford Limited.

There are 3 main consequences of dam failure, which are the backbones of our national dam insurance program.

Economic Consequences

This is addressed through the insurance feature of the program where we help dam owners cover the cost of repairing the dams and compensating citizens for the property losses and infrastructure damage.

Public Safety Consequences

The Public Engagement component of our program, whereby citizens, dam owners and operators are offered trainings and preventive measures, help minimise the consequences in case of dam failures.

Environmental Consequences

We advocate for a Research & Development budget for AI to help monitoring and predicting perils. We also propose a set of possible measures for specific disasters in each region to mitigate dam failures.

8.4. Financial Analysis

8.4.1. Pricing Methodologies

As we don't have any claims data yet, we will price premium based purely on dam owners' exposure to risk.

We assume that the Probability of Failure is the same across the 10-year period because we didn't have the data needed to model the change in this variable. Thus, the Annual Probability of Failure is the 10-year geometric mean of the Probability of Failure provided in the dataset.

Expected Repair Cost = `Loss given failure – prop (Qm)` * `Annual Probability of Failure`

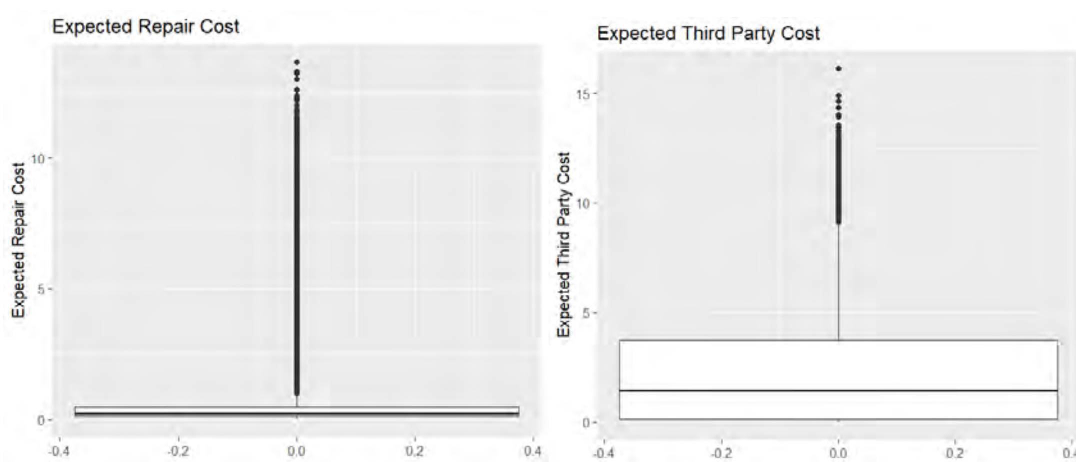
Expected Third Party Cost = `Loss given failure – liab (Qm)` * `Annual Probability of Failure`

These are proxies for risk exposure of each dam owners. We then regress these 2 variables against our attributes to get the predicted risk exposure for each dam, also known as pure premium.

8.4.2. Pure Premium Modelling

Our predictors include: Region, Regulated Dam, Primary Purpose, Primary Type, Size (km3), Age, Number of Modification, Spillway, Inspection Frequency, Years from Last Inspection, Distance to Nearest City (km), Hazard, and Assessment.

All the numeric variables are scaled before fitting to the model to avoid bias.

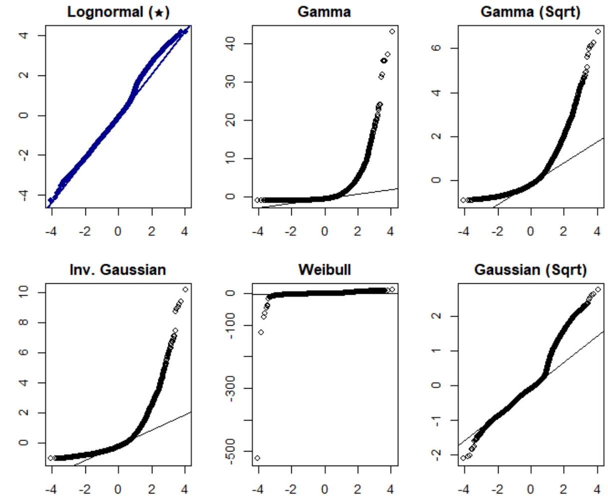


Dam Repair Model

We compared 6 GLM models in terms of RMSE and QQ-Plot for the residuals to choose our model. Machine Learning Models were also considered (Random Forest, Gradient Boosting, XGBoost, Neural Network, SVM, k-Nearest Neighbour). Even though they gave better predictions (lower RMSE), for transparency and regulatory requirements, we decided to proceed with GLMs.

Because the data is heavily right-skewed, we performed some transformation (log/square root) and fit heavy-tailed distributions such as Gamma and Log Normal.

Model	RMSE
Gamma	4.258027
Gamma (sqrt)	3.791971
Inverse Gaussian	Inf
Weibull	4.205034
Lognormal	**2.686115**
Gaussian (sqrt)	1.785015

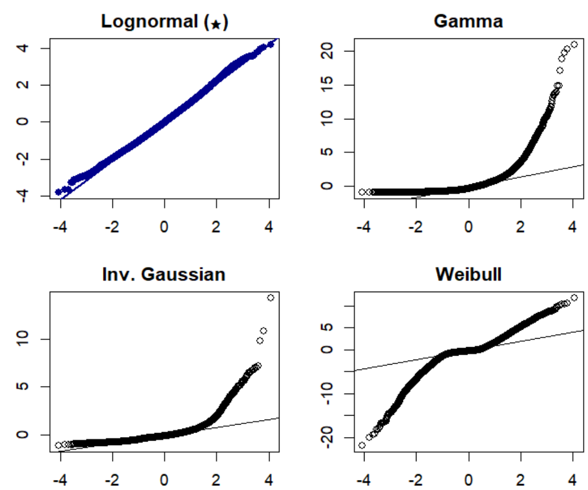


Even though Gaussian with square root transformation gave lower RMSE, we chose Log Normal because it gave us the best QQ Plot of the residuals, meaning that the residuals are normally distributed.

Third Party Cost Model

We applied the same process with the Expected Third-Party Cost and obtained the following result:

Model	RMSE
Gamma	2.538588
Lognormal	**2.556647**
Inverse Gaussian	4.203592
Weibull	2.552288



As Log Normal has acceptable RMSE and best QQ Plot again, we chose Log Normal as our final model.

Final Model Summary

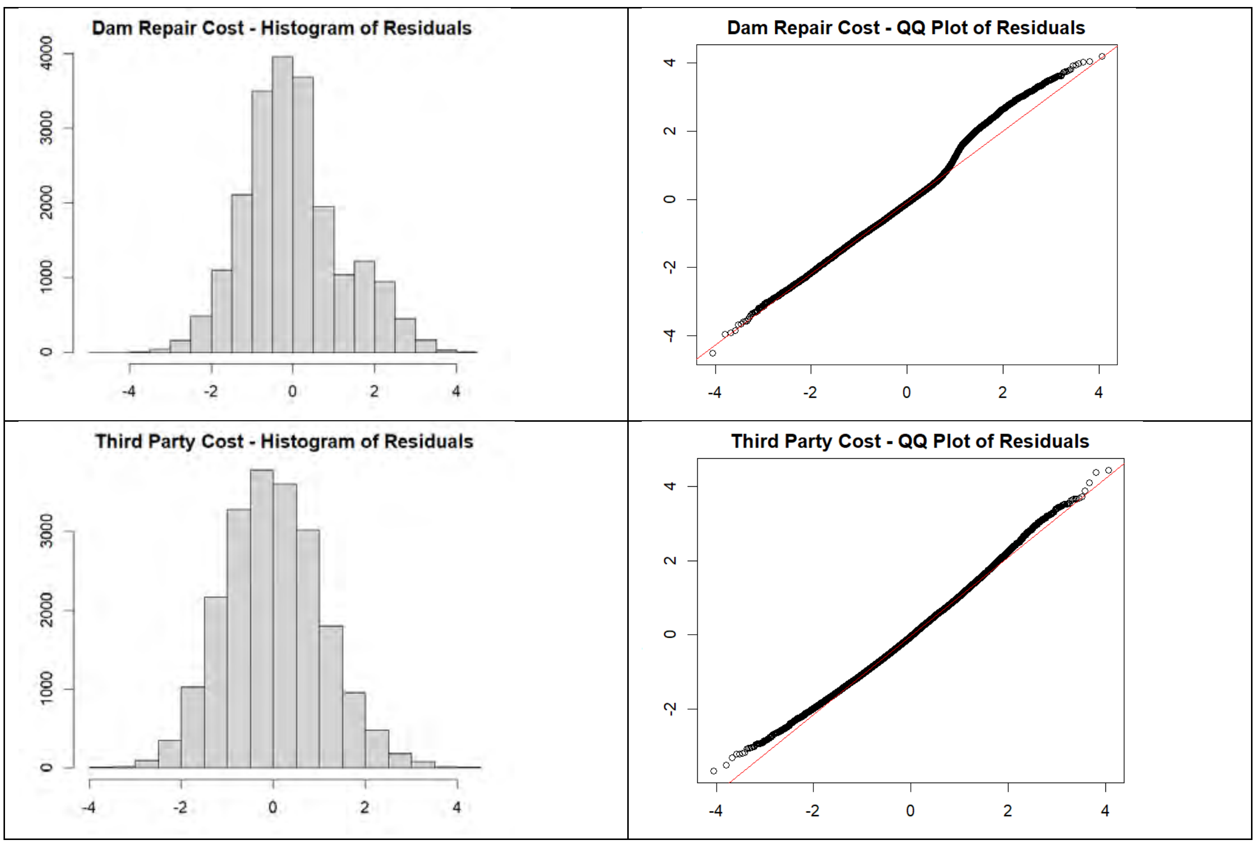
	Log (Repair Cost)			Log (Third Party Cost)		
Predictors	***Estimates***	***std. Error***	***p***	***Estimates***	***std. Error***	***p***
(Intercept)	0.20	0.20	0.323	0.85	0.18	**<0.001**
Region [Lyndrassia]	-0.26	0.03	**<0.001**	0.45	0.03	**<0.001**
Region [Navaldia]	0.08	0.03	**0.006**	-0.82	0.03	**<0.001**
Regulated Dam [Yes]	0.19	0.02	**<0.001**	0.71	0.02	**<0.001**

Primary Purpose [Fire Protection, Stock, Or Small Fish Pond]	-0.06	0.09	0.476	0.00	0.08	0.992
Primary Purpose [Fish and Wildlife Pond]	0.45	0.10	**<0.001**	-0.93	0.09	**<0.001**
Primary Purpose [Flood Risk Reduction]	0.31	0.09	**<0.001**	-0.74	0.08	**<0.001**
Primary Purpose [Grade Stabilization]	0.21	0.09	**0.024**	-1.58	0.08	**<0.001**
Primary Purpose [Hydroelectric]	0.86	0.11	**<0.001**	-0.39	0.10	**<0.001**
Primary Purpose [Irrigation]	0.39	0.09	**<0.001**	-0.28	0.08	**<0.001**
Primary Purpose [Navigation]	1.29	0.26	**<0.001**	-0.49	0.23	**0.033**
Primary Purpose [Other]	0.22	0.09	**0.017**	-0.34	0.08	**<0.001**
Primary Purpose [Recreation]	0.13	0.08	0.117	-0.22	0.08	**0.003**
Primary Purpose [Tailings]	0.65	0.13	**<0.001**	-0.74	0.12	**<0.001**
Primary Purpose [Water Supply]	0.27	0.09	**0.002**	-0.53	0.08	**<0.001**
Primary Type [Buttress]	-0.55	0.23	**0.015**	-0.02	0.20	0.932
Primary Type [Concrete]	-0.61	0.19	**0.002**	0.43	0.17	**0.013**
Primary Type [Earth]	-0.62	0.18	**0.001**	0.40	0.16	**0.013**
Primary Type [Gravity]	-0.13	0.19	0.495	0.92	0.17	**<0.001**
Primary Type [Masonry]	-0.31	0.34	0.363	0.54	0.30	0.073
Primary Type [Multi-Arch]	0.23	0.39	0.544	0.42	0.34	0.223
Primary Type [Other]	-0.63	0.21	**0.003**	0.22	0.19	0.241
Primary Type [Rockfill]	-0.09	0.20	0.664	0.51	0.17	**0.003**
Primary Type [Roller-Compacted Concrete]	-0.09	0.37	0.814	0.70	0.32	**0.030**
Primary Type [Stone]	-0.70	0.28	**0.013**	-0.32	0.25	0.200
Primary Type [Timber Crib]	0.50	0.39	0.199	0.48	0.35	0.163
Size km3	0.07	0.01	**<0.001**	-0.01	0.01	0.338
Age	0.07	0.01	**<0.001**	0.11	0.01	**<0.001**
Number of Modification	0.13	0.01	**<0.001**	0.00	0.01	0.970
Spillway [Uncontrolled]	-0.54	0.05	**<0.001**	0.14	0.05	**0.002**
Inspection Frequency	-0.19	0.01	**<0.001**	0.01	0.01	0.193
Years from Last Inspection	-0.00	0.00	**<0.001**	0.00	0.00	**0.019**
Distance to Nearest City km	0.05	0.01	**<0.001**	-0.33	0.01	**<0.001**
Hazard [Low]	-0.92	0.03	**<0.001**	-1.97	0.02	**<0.001**
Hazard [Significant]	0.07	0.03	**0.031**	-0.09	0.03	**0.002**

Hazard [Undetermined]	-0.97	0.33	**0.003**	0.82	0.30	**0.005**
Assessment [Not Available]	0.74	0.06	**<0.001**	0.40	0.05	**<0.001**
Assessment [Not Rated]	0.12	0.03	**<0.001**	-0.21	0.03	**<0.001**
Assessment [Poor]	0.10	0.06	0.065	0.11	0.05	**0.028**
Assessment [Satisfactory]	0.02	0.03	0.523	-0.65	0.03	**<0.001**
Assessment [Unsatisfactory]	0.33	0.06	**<0.001**	0.16	0.05	**0.005**
Observations	20804					

We exclude 2 observations from the original datasets. 1 is the observation with Last Inspection Date in 2031, and the other is the observation with size of 97km3 in our portfolio of covered dams because it significantly distorted the prediction distribution. More information would be required to determine whether this is an error and how to fix them.

Residual Diagnostics



The residuals are normally distributed, and the QQ Plots are acceptable for both models.

8.4.3. Expenses

Expense	Total Amount	Rationale
Assessment Grants	Q17,353,000	We find the number of dams that qualify for the grant and multiply that with the grant amount.
Educational & Public Engagement Program	Q1,000,000	Calculated based on the USA – NDSP State Assistance Grant Program. See details below.
Operational/Administration Cost	Operational costs: 5% Staffing & HR: 3% Regulatory & Compliance: 1% Technology & Infrastructure Maintenance: 2%	Details of calculation in Appendix 8.4. - Assumptions
Reinsurance Cost	Coupon rate: 7% Issuance fee: 0.01% Management fee: 0.02%	Cost of cat bond issuance. Term of 5 years.

Assessment Grants

Range of Size (m3)	Amount	Number of dams qualified	Total
0 – 1.5 million	Q1,000	2208	Q2,208,000
1.5 – 10 million	Q5,000	1319	Q6,595,000
>10 million	Q10,000	855	Q8,550,000

Public Engagement

The costs are based on the **USA - NDSP State Assistance Grant Program**
"The primary purpose of the National Dam Safety Program (NDSP) State Assistance Grant Program is to provide financial assistance to the states for strengthening their dam safety programs."

Fiscal Year	Total State Assistance Grant	State	Population	Grant Per Capita	Total for Tarrodan (95m population)
2023	$6.25 million	49 states and Puerto Rico	332,333,146	$0.01880643	$1.7866 million
2022	$10.854 million	49 states and Puerto Rico	330,746,672	$0.032816657	$3.1176 million
2021	$5.815 million	48 states and Puerto Rico	321,850,820	$0.018067377	$1.7164 million
2020	$6.15 million	49 states and Puerto Rico	329,021,331	$0.018691797	$1.7757 million
2019	$6.8 million	49 states and Puerto Rico	325,824,283	$0.020870145	$1.9827 million

We take the average of the previous 5 years (excluding 2024 because it's an outlier) as a proxy for Tarrodan's program. This gives an estimate of $2.08 million, translating to 1.98 Qm.

However, the states use NDSP funds for the following types of activities, which include both Public Engagement and Preventive Measures:

- "Dam safety training for state personnel" (2.2.2 Public Engagement)
- "Increase in the number of dam inspections" (2.2.1 Preventive Measures)
- "Increase in the submittal and testing of Emergency Action Plans" (2.2.1 Preventive Measures)
- "More timely review and issuance of permits" (2.2.1 Preventive Measures)
- "Improved coordination with state emergency preparedness officials" (2.2.2 Public Engagement)
- "Identification of dams to be repaired or removed" (2.2.1 Preventive Measures)
- "Conduct dam safety awareness workshops and creation of dam safety videos and other outreach materials" (2.2.2 Public Engagement)

We are only interested in the cost of the Public Engagement component. Assuming 50% of total cost is spent on this component, we get around **1Qm** as the cost of our educational and training program.

Instrumentation	Risk / Failure Monitoring	Cost	Difficulty of Installation	Difficulty of Automation	Required Maintenance	Applicability to DOW State- Owned Dams
Seepage Weirs	Monitors one failure mode (Internal Erosion/Piping)	Moderate cost	Medium	Medium	Medium	Medium – limited to dams with existing toe drains
Flow Monitors	Monitors one failure mode (Internal Erosion/Piping)	Moderate cost	Medium	Low	Medium	Medium – limited to dams with existing toe drains
Soil Extensometers	Monitors slope instability (due to static, seismic, or rapid drawdown)	Approximately $3,000 in material cost (assumes 3 sensors in series with cables run 500 feet) and $3,000 in installation cost[1]	Medium – requires shallow trench to install	Low	Medium	High – can be installed on any earthen dam to monitor for movement
Vibrating Wire Piezometers	Monitors slope instability (due to static, seismic, or rapid drawdown)	Approximately $1,500 in material cost (assumes 2 piezometers and cable run 200 feet) and $3,000 in installation cost[1]	Low for sites that already have piezometers (i.e. automating existing instrumentation) and High for sites that do not have piezometers (i.e. installing new instrumentation)	Low	Medium	Low – applicable to all earthen dams, however it is costly to install where there are not existing piezometers. Most state-owned dams do not have piezometers.
In-Place Slope Inclinometers	Monitors slope instability (due to static, seismic, or rapid drawdown)	Approximately $8,000 in material cost (assumes a 50- foot deep inclinometer) and $2,500 in installation cost[1]	Medium – can be installed in a day with a two-man crew	Low	High	Low – applicable to all earthen dams, however it is costly to install where there are not existing slope inclinometers. Most state- owned dams do not have this instrumentation.
Low-Pressure Transducers	Monitors three failure modes (Overtopping of Spillway or Crest) and Rapid Drawdown	Approximately $1,500 in material cost (assumes a 50- foot deep inclinometer) and $2,500 in installation cost[1]	Medium – can be installed in a day with a two-man crew	Low	Medium	High – applicable to most state-owned dams for reading water levels
IoT Flood Sensors	Monitors three failure modes (Overtopping of Spillway or Crest) and Rapid Drawdown	Approximately $1,000 each in material cost, approximately $3,000 in installation cost	Medium	Low	Medium	High – applicable to most state-owned dams for reading water levels
Fiber Optic	Monitors slope instability (due to static, seismic, or rapid drawdown)	Moderate cost	High	Low	Medium	High – applicable to most state-owned dams
Ultrasonic Sensors	Monitors three failure modes (Overtopping of Spillway or Crest) and Rapid Drawdown	Moderate cost	Medium	Low	Medium	High – applicable to most state-owned dams for reading water levels
Drone	Monitors slope instability (due to static, seismic, or rapid drawdown) and for Internal Erosion/Piping	$2,000 - $10,000 (equipment only) but can be used at multiple sites	Low	Medium	Medium	High – applicable to most state-owned dams

[1]Does not include cost of readout box (~$7,800 in materials and labor, can be used by multiple instruments)

Note. Adapted from “Report of Findings: Kentucky Division of Water - Critical Infrastructure and Flood Risk Management Innovation for Dam Safety Monitoring” by the U.S. Department of Homeland Security, Science and Technology Directorate, 2020, p.12 (https://www.dhs.gov/sites/default/files/publications/21_0202_st_low_cost_flood_sensors_innovation_for_dam_safety_monitoring.pdf).

8.4.4. Final Premium & Base Case Result

Final Premium = (Pure Premium + Risk Loadings + Expenses) * (1+ Contingency Loadings)

Inflows Summary

Year	Pure Premium	Risk Loading	Expenses Loading	Contingency Loadings	Final Premium	CAT Bonds	Expected Inflows
0	-	-	0.9167	-	-	-	-
1	33656.7518	6604.7855	4349.8337	30%	57,995.97	44,321.72	102,317.70
2	34426.6472	6742.9875	4705.9981	30%	59,638.32	-	59,638.32
3	33280.9948	6498.3629	4593.9764	30%	57,685.33	-	57,685.33
4	32232.4888	6279.7983	4436.6939	30%	55,833.68	-	55,833.68
5	31293.0643	6089.4956	4577.7564	30%	54,548.41	-	54,548.41

Outflows Summary

Year	Claims Payments	Expenses	Assessment Grants + Educational Program	Expected Outflows
0	0	0.92	17.85	-18.77
1	59,168.97	4,349.83	0.51	-63,519.32
2	61,756.37	4,706.00	-	-66,462.37
3	62,970.63	4,593.98	-	-67,564.61
4	62,788.65	4,436.69	-	-67,225.34
5	62,840.02	4,577.76	-	-67,417.78

Cashflows Summary

Year	Net Cashflow	PV
0	-18.77	-18.77
1	38,798.38	37,933.49
2	-6,824.05	-6,523.20
3	-9,879.27	-9,233.21
4	-11,391.67	-10,409.37
5	-12,869.37	-11,497.51
Total	-2,184.75	251.44

Contingency Loadings

In the CAS's database, research by Gary Venter on contingency loadings, namely "PROFIT/CONTINGENCY LOADINGS AND SURPLUS: RUIN AND RETURN IMPLICATIONS", states:

"The profit/contingency loading in the insurance rate serves two purposes: (i) to aid solvency by absorbing some degree of fluctuation in loss experience and (ii) to provide a suitable average return to the underwriter."

Furthermore, Venter highlights the existence of an equilibrium point where:

"(a) surplus and the loadings together give sufficient protection against insolvency, (b) the loading is high enough to yield the desired average return rate and (c) for any lower loading amount, any surplus selected will violate either (a) or (b)."

While we did not explicitly implement this equilibrium point, our approach ensures that contingency loadings are structured to mitigate risk and maintain financial stability. The loadings were carefully calibrated to align with market conditions and the program's objectives, targeting an overall financial position close to break even. The final contingency loading was decided to be 30% in the first 5 years of the program, when we lack claim data for pricing, and will be adjusted once the program has been established. This approach allows for effective risk management while ensuring the program remains sustainable over time.

What will happen to the budget surplus?

We have considered several options:

- Use the excess funds to cushion against future extreme claims experience (in years where there will be lots of dam failures).

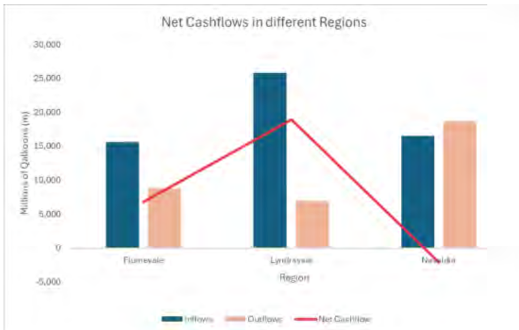
- Adjust future premiums to ensure affordability and prevent overcharging policyholders based on assessment of budget from this year and previous year.

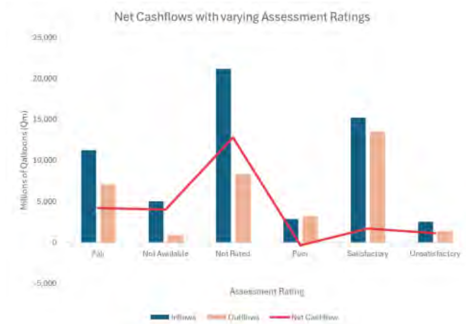
- Redirect the funds to disaster relief funds and subsidies etc.

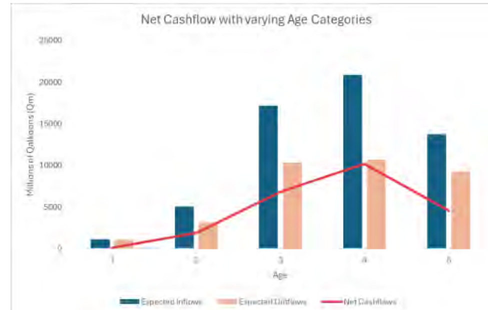
We decided to redistribute the surplus funds to policyholders whose dams don't fail during the first 5-year period. This mechanism rewards long-term contributors, ensuring that earlier cohorts of policyholders benefit from the surplus they helped build.

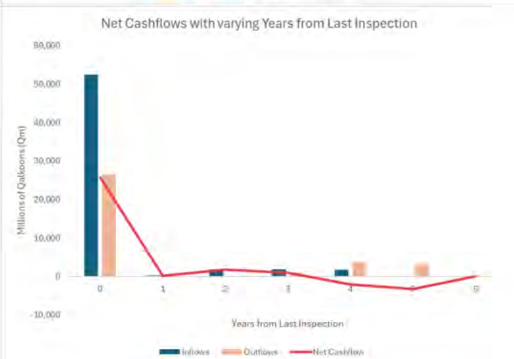
8.4.5. Scenarios Analysis

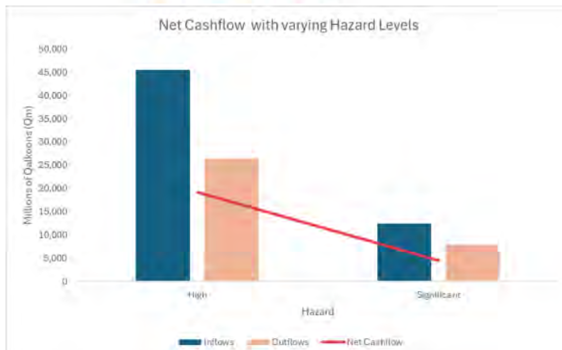
Cash Flows by Attributes





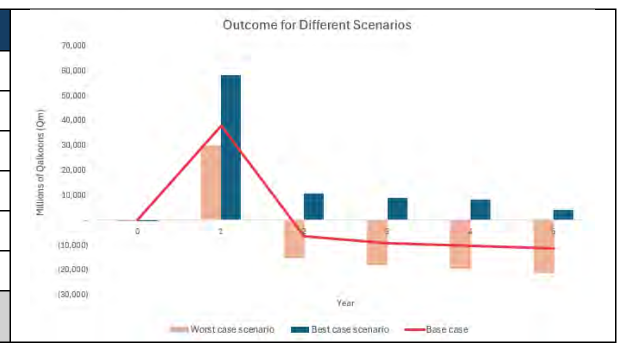






Scenarios Analysis

Year	Worst case	Best case	Base case
0	(18.77)	(18.77)	(18.77)
1	29,767.17	58,253.08	37,933.49
2	(15,223.96)	10,515.49	(6,523.20)
3	(17,857.55)	8,986.45	(9,233.21)
4	(19,466.95)	8,317.77	(10,409.37)
5	(21,245.50)	4,011.83	(11,497.51)
NPV	(44,045.57)	90,065.84	251.44



Our scenario analysis provides a comprehensive view of potential financial outcomes by examining best-case, worst-case, and base-case scenarios. The best-case and worst-case scenarios represent the extremes, derived from our failure simulations: the worst-case scenario is based on the highest loss observed in 1,000 simulations, while the best-case scenario reflects the lowest claims payment the insurer needs to pay out.

For consistency, all inflows remain unchanged across scenarios, with the key variable being the claims payments. As a result:

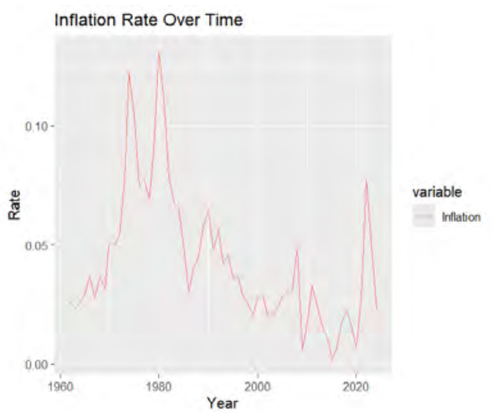
- Worst-case scenario: A significant claims payout leads to a negative net cash flow of 44 billion Qalkoons.
- Best-case scenario: Minimal claims result in a positive cash flow of 90 billion Qalkoons.

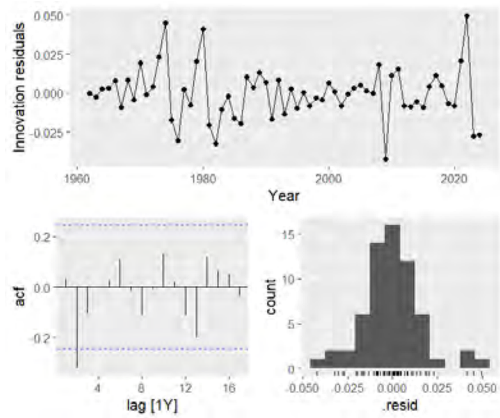
- Base-case scenario: The mean total loss from 1,000 dam failure simulations yields a net cash flow of 251.44 million Qalkoons, providing a balanced estimate of expected conditions.

While this profit is expected to be moderate, it plays a crucial role in strengthening the insurance program's financial stability. Surpluses can be reinvested into the program to establish reserves, reducing reliance on annual premium collections for claims fulfillment. This buffer enhances long-term sustainability, ensuring adequate coverage in high-claim years. Additionally, consistent profitability could provide opportunities to offset expenses, such as reinsurance costs on catastrophe bonds, and may even lead to premium reductions if financial conditions allow.

8.5. Assumptions

Inflation Rate





After differencing it once, the inflation rate is a white noise series. Thus, we use ARIMA(0,1,0), or naïve forecast, for the next 5 years. As the inflation fluctuated a lot and decreased sharply after Covid, we believe this is a reasonable estimate.

Third Party Losses Reduction Rate

The potential savings resulting from public engagement in disaster mitigation efforts have been identified in relation to bushfire management, and a more conservative estimate can be applied to dam failure scenarios.

Regarding life loss savings, the cost of life loss per CFA region is $41.5 million for Community Fireguard (CFG) participation and $69.2 million for non-CFG participation, resulting in a savings of $27.7 million (Gibbs et al., 2015). This represents an approximate 40% reduction in life loss costs.

In terms of property loss savings, the expected cost of property loss per household in the event of a major bushfire is $117,379 for regular CFG participation and $194,375 for non-CFG participation across bushfire regions, translating to a 39.6% reduction in property loss costs (Gibbs et al., 2015).

Assuming that third-party costs in our dataset include 40% public goods and 60% private goods. With the more challenging reduction of public goods losses, which could be reasonably estimated at a 20% reduction, the overall savings rate is still substantial at 32%. Given the lower expected impact of public engagement on dam failures compared to bushfires, a 20-25% reduction in losses for dam failures is deemed reasonable. Additionally, considering the nature of public engagement, it is expected that the reduction in losses will be compounding and gradual. Therefore, it is anticipated that reductions will be around 7% in the third year, and 7.5% in both the fourth and fifth years, with the first two years dedicated to program implementation.

Dam failure risks are less likely to be influenced by public engagement than bushfires for several reasons. First, dam failures tend to occur suddenly and with little warning, making it difficult for public engagement to significantly affect outcomes once an event occurs. In contrast, bushfires can often be forecasted and managed proactively, allowing for greater public involvement in mitigation efforts. Second, the risk of dam failure is more closely linked to structural integrity and engineering solutions, such as regular dam inspections and maintenance, which are beyond the scope of public engagement. On the other hand, bushfires are more directly influenced by human actions, including fire prevention measures and public readiness. Lastly, while public engagement plays a vital role in bushfire prevention, preparation, and response, public involvement in dam failure scenarios is typically limited to awareness and evacuation protocols, leaving less room for mitigation compared to the proactive nature of bushfire management.

Spillway Control Rate

We simulated the control rate with the following function:

```
s_curve <- function (x, total_years) {
  1 / (1 + exp(-5 * ((x / total_years) - 0.5)))
}
```

The S-curve transition function is used to model the gradual implementation of spillway control measures over a five-year period, with the goal of reaching 100% control by the end. The rationale for using this curve is that the adoption of control measures typically starts slow, accelerates as progress is made, and then slows down again as the system nears full implementation. This pattern reflects how new systems are often adopted, where there is initial hesitation, followed by a phase of rapid growth, and finally a stabilisation period.

Risk Loadings

This assessment is based on regional disaster risks. Floods are the most frequent cause of dam failures, followed by earthquakes and tsunamis (Statista, 2025). The NFIP's Risk Rating 2.0 applies up to 0.1% geographic risk loading per property, but since dam failures impact entire communities, we set regional loadings between 10% and 30%. Flooding and overflow from heavy rains are the leading causes of dam failures, making Flumevale the highest-risk region. Avalanches can also contribute to overflows, while earthquakes may compromise structural integrity, increasing the likelihood of failure. Given that Lyndrassia occasionally experiences both, a 20% risk loading is appropriate. Meanwhile, Navaldia's coastal location exposes it to tropical storms and tsunamis, but as these events are relatively rare, its risk loading is set at 10%.

Administration Costs

The administrative costs are derived from the expense structure of the NFIP's Write-Your-Own (WYO) program, as detailed in the Affordability of National Flood Insurance Program Premiums: Report 1 (National Academies of Sciences, Engineering, and Medicine, 2015). The NFIP allocates 12.5%–13.5% of written premiums to company expenses, which include operational costs, staffing, compliance, and technology expenses. Additionally, FEMA's analysis accounts for costs associated with claims processing and regulatory compliance. Following the framework, our cost allocation are expressed as a % of pure premium as follows:

- Operational costs (5%): Reflecting general business expenses, including office operations and service delivery, in line with NFIP's company expense structure.
- Staffing & HR (3%): Based on the personnel-related expenses required to administer policies effectively.
- Regulatory & Compliance (1%): Accounting for legal, licensing, and reporting obligations, similar to the NFIP's handling of regulatory costs.
- Technology & Infrastructure Maintenance (2%): Necessary for underwriting, claims processing, and digital transformation, comparable to NFIP's investments in program administration.

Other Assumptions

The Probability of Failure used in this model is based on independent probabilities provided in the dataset. These probabilities are assumed to account for key dam characteristics, including region, year of construction, spillway type, inspection frequency, and assessment ratings. However, in practice, dam failures are not always independent events. A single dam failure can trigger flooding that places additional stress on downstream dams, increasing their likelihood of failure. Ideally, this cascading effect should be captured using an Adjusted Probability of Failure that reflects interdependencies. Due to the absence of data on hydrological connectivity (e.g., river networks, upstream-downstream relationships), our model assumes independence between dam failures. As a result, potential cascading failures are not explicitly reflected, although they may occur in reality.

8.6. Other Risk & Risk Mitigation

Qualitative Risks

Risk	Description	Mitigation Strategy
Political Risk	Changes in political leadership or government priorities could affect long-term funding and commitment.	Secure multi-year legislative backing and build support from state governments to ensure program continuity.
Implementation Risk	Difficulties in rolling out the insurance program, particularly in engaging dam owners and ensuring compliance.	Phased implementation with continuous monitoring, feedback loops, and adaptive policy adjustments.
Ownership & Liability Risk	Unclear legal responsibility for dam failures, particularly for privately owned or abandoned dams.	Federal government will take ownership of all abandoned dams that are highly and significantly hazardous. All other dams that are not currently owned will be transferred to state government/private or decommissioned. Strengthen legal frameworks clarifying liability and enforce adherence through mandatory compliance checks.

Quantitative Risks

Risk	Description	Mitigation Strategy
Data Accuracy Risk	Missing or outdated dam assessment data may lead to misclassification of risk levels.	Provide grants for dam assessment to improve data collection and refine risk models. Conduct sensitivity/scenarios analysis to account for uncertainties in the modelling process.
Funding & Reserve Risk	Over-reliance on government subsidies in the early years could create long-term budgetary constraints.	Implement a gradual transition from government-backed subsidies to self-sustaining premium funding.
Environmental Risk (Expanded)	Natural and human-induced environmental changes that may affect dam safety and increase the potential for financial losses, including extreme weather events, seismic activity, altered rainfall patterns, and changes in land use or soil conditions. Such factors can place stress on dam infrastructure, compromising its integrity.	Set up early warning systems, investing in the infrastructure that prevents or mitigates the risks of dam failure with frequently inspections. Monitoring of Critical Components: Use of technology such as remote sensing, sensors, and drones can help monitor the structural health of the dam, including leakage, pressure buildup, and vibration levels. Strengthening embankments and expand spillway capacities. More measures can be found in the table below.

Specific Measures for different disaster types

Disaster Type	Required Improvements	Approximate Cost	Timeline	Personnel Required	Expected Benefits
Tsunami	- Construct higher, reinforced spillways to withstand tidal surges. - Improve dam base with more robust foundation materials (concrete/steel reinforcements). - Install flood barriers.	$10-15 million	2-3 years	50-70 engineers & labourers	Prevents structural failure from surge impact; reduces risk of breach.
Fire Disaster	- Install fire-resistant coatings on external parts of the dam (e.g., spillways, access roads). - Create firebreak zones around the dam. - Ensure access for emergency response teams.	$2-5 million	1-2 years	15-25 fire safety engineers	Reduces fire damage risk to the dam and access routes; enhances safety.
Flooding & Erosion	- Reinforce dam embankments with additional erosion control measures (vegetation, riprap). - Strengthen spillway and water diversion infrastructure. - Enhance sediment management.	$5-8 million	1-2 years	40-50 civil engineers & labourers	Prevents dam overflow or erosion during heavy rainfall; mitigates failure.
Seismic Activity	- Retrofit the dam with seismic-resistant engineering (base isolation or reinforcement). - Conduct soil stabilization around the dam foundation. - Strengthen internal structural integrity.	$20-30 million	3-4 years	100-150 seismic engineers & labourers	Increases dam stability during earthquakes; reduces risk of collapse.
Avalanche	- Install avalanche barriers on upstream sides. - Reinforce surrounding terrain to prevent	$5-10 million	2-3 years	30-50 engineers & labourers	Prevents debris flow from affecting dam integrity; safeguards dam.

	landslides that could destabilize the dam. - Create drainage systems to redirect runoff from avalanche zones.				

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