Improving Coastal Infrastructure Resilience by Bridging Risk Perception of Engineers and Maintenance Decision-Making

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Abstract:

Dam safety is not just about engineering; it also depends on how people perceive risk, make decisions, and allocate resources. While engineers usually analyze dam failures based on technical and physical factors, human and behavioral dynamics play a major role in infrastructure resilience. This study explores how risk perception and maintenance decisions interact by using a system dynamics approach to understand the relationships between dam owners, engineers, and policymakers. Based on interviews and a survey conducted among U.S.-based engineers, this study identifies key challenges in dam upgrades. Using information and physical flows, this work employs a system dynamics method and presents a stock-flow model for strengthening dam resilience. In order to evaluate dam resilience and the engineering community's perception of risk, causal linkages are established for the physical, financial, climate policy, and regulatory layers. While this study focuses on dam safety, the proposed framework and findings are highly relevant to other critical infrastructure systems, such as coastal flood defenses and levees, which face similar socio-technical challenges of deterioration, financial constraints, and fluctuating risk perception. Findings show that dam owners, as the main decision-makers, often focus on short-term financial priorities rather than long-term resilience. Engineers' risk perception influences their recommendations for maintenance budgets, but financial constraints, political shifts, and regulatory instability frequently delay necessary investments. Using causal loop modeling and a stock-flow framework, this research shows how risk perception can change over time, affecting funding decisions that will result in cycles of neglect and urgent upgrade. This study focuses on the need for proactive maintenance strategies instead of reactive fixes after disasters. Policy recommendations include regular risk awareness training for engineers, long-term funding structures for maintenance, and reducing political influence in infrastructure investment decisions. Understanding how human factors shape infrastructure safety can help develop better policies to ensure long-term infrastructure resilience.

1. Introduction

The built environment reflects the ideas and decisions of people over time. Various agents and stakeholders interact with one another and influence the development of our cities, with engineers playing a key role in designing and constructing urban spaces. Understanding the influences on their decision-making, including codes and standards, is important for improving city planning and resilience. The impact of hazards often depends on the choices we make. As climate change accelerates, reassessing our decision-making frameworks and regulatory approaches can help us better adapt to disruptive events and better respond to challenges. However, significant change requires a deeper understanding of human behavior. Research on human factors is now a key part of safety assessments in different engineering fields (Perrow, 2011). The same approach is being used in dam engineering, where human limitations, quick decision-making shortcuts, and risk perception affect how well safety measures work (Svenson, 2000). Dam failures have historically led to significant consequences, including loss of life, property and ecological damage, and environmental harm. Engineers often investigate dam breakdowns based on physical variables and mechanisms, which is understandable given their technical expertise (Alvi & Alvi, 2023). However, dam construction and governance involve both physical and human variables, together termed a sociotechnical system, which contributes to dam safety and failure. Some studies explored how organizational attitudes influence infrastructure management decisions during interruptions (McAlister et al., 2024). Research on dam safety highlights that while structural failures can be caused by physical issues, human mistakes in decision-making, maintenance, and management also play a major role in disasters (Kirschke & Newig, 2017; Paté-Cornell & Murphy, 1996). Recent investigations into dam failures, like the Oroville Dam spillway incident, show that a mix of technical errors, weak regulations, and poor decision-making by institutions can lead to serious social and environmental damage (Schweiger, 2018). Despite recent advances, understanding and integrating the specific characteristics of decision-makers such engineers, owners, and politicians is crucial for making resilient and sustainable decisions (Ma et al., 2021). However, infrastructure projects, including dams, are often influenced by financial and organizational dynamics that extend beyond technical considerations. Projects may slow down or come to a halt because lenders' risk-reduction processes are designed to prioritize their own interests over the project's needs (Olatunji et al., 2024). Economic constraints and risk-mitigation strategies influence not only project timelines and costs but also safety measures and long-term resilience planning (Altshuler & Luberoff, 2004; Flyvbjerg et al., 2003). Research has shown that political (Boin & Lodge, 2016; May, 2007) and economic pressures often lead to suboptimal decision-making in large-scale infrastructure projects, prioritizing immediate cost savings over long-term sustainability (Ansar et al., 2014). Additionally, project owners' personal finances and the number of lenders involved in a single project are linked to cost overruns. Regulatory failures in dam management have been documented in cases where outdated policies, insufficient oversight, and conflicting stakeholder interests have contributed to safety risks (Moynihan, 2009).

These financial and managerial complexities promote the need to examine the decision-making processes of key stakeholders, such as engineers, project owners, and policymakers. Human limitations influence every aspect of cognition, judgment, and decision-making. As dam engineering has advanced, so has our knowledge of the physics that govern dam behavior, resulting in better design and construction techniques. However, because human decision-making occurs at every stage of a dam's lifecycle, including design, construction, operation, inspection, monitoring, evaluation, maintenance, and repair, it is apparent that human factors play a crucial role in dam collapses. In recent decades, human factors research has become increasingly important in forensic investigations and dam safety management (Delpasand et al., 2021; Jamsawang et al., 2011; Zarei et al., 2023). For example, probabilistic risk assessments and resilience-based design approaches integrate human factors into engineering decision-making, leading to more adaptive and robust infrastructure systems (Aven, 2016; Linkov et al., 2018).

2. System dynamics framework for risk perception and infrastructure resilience

2.1 Problem statement

This study explores the feedback mechanisms among the engineering community that influence dam resilience, focusing on how physical degradation can interact with financial constraints, shifts in risk perception, politically-driven regulations and exogenous factors, which can contribute to systemic failures. Hence, the motivating research question addressed in this paper is as follows: What interactions occur between the financial decisions of dam owners for infrastructure maintenance, risk perception of engineers, and dam deterioration dynamics, and how do these interactions influence infrastructure resilience? Using system dynamics approach, we identify key leverage points for improving maintenance and resilience policies and ensuring long-term dam sustainability. Based on the problem statement, this paper will discuss three main themes as follows:

- Decision-making dynamics between engineers and dam owners.
- Feedback loops related to risk perception, maintenance, and disaster response by engineers and stakeholders.
- Policy and funding implications of reactive and proactive maintenance for resilience.

2.2 Narratives based on 18 interviews with practitioners

The causal relationships among stakeholders in this study are derived from interviews conducted with 18 experts in the field of flood control infrastructure. The interviews were conducted in 2022 as part of a larger NSF-funded research project. IRB approval for human subject research was obtained prior to conducting interviews. After analyzing the transcripts and extracting relevant quotes related to the problem statement, we present a narrative on the reasons why dams fail, the key social factors contributing to such failures, and strategies for their prevention and mitigation. Dams play a critical role in water management, flood control, and energy production. However, their resilience depends on sustained investment in maintenance and timely interventions to upgrade and prevent deterioration (Jamsawang et al., 2011).

These dynamics are not confined to dams. In coastal engineering, levees and seawalls are similarly subjected to progressive deterioration, driven by environmental stressors such as saltwater corrosion and continuous wave action. Climate change and sea-level rise further exacerbate these processes, functioning as critical threat multipliers. Nevertheless, comparable financial and political constraints frequently postpone essential maintenance and structural upgrades until after catastrophic failure has occurred, as evidenced in post-event analyses of flood protection systems following Hurricane Katrina During the interviews, some of the engineers disclosed that the decision-making process of dam owners regarding budget allocation is central to determining whether dams receive adequate maintenance to remain in good condition and ensure long-term resilience. However, budget decisions depend on various factors, such as politics, risks, and regulations (Ibrahim et al., 2023; Olatunji et al., 2024). While interview narratives provide valuable insights into the lived experiences of engineers and dam owners, they also reveal that these interactions are highly dynamic and nonlinear. Owners rely on information from engineers, whose perception of dam-related risks influences their recommendations. When engineers perceive higher risk due to poor dam conditions, they may advocate for increased maintenance funding. The effectiveness of this process depends on how well engineers communicate risk to decision-makers.

Additionally, dam deterioration is a dynamic process, progressing from good to fair to poor condition over time due to natural wear, aging infrastructure, and inadequate maintenance. Without intervention, this deterioration increases the risk of failure, reinforcing the need for risk-aware decision-making. A reinforcing loop emerges following disasters, as catastrophic failures heighten engineers' risk perception, leading to stricter regulations and greater maintenance investments over time. However, over time, maintenance priorities may shift, funding may decrease, and deterioration may accelerate, ultimately increasing the risk of future failures. This study presents a causal loop modeling framework to analyze the interactions among three key factors: (1) owners' decision-making and maintenance budget allocation, (2) engineers' risk perception and its influence on decision-making, and (3) the physical deterioration of dams and its impact on risk perception. To support the storytelling, relevant quotes from interviews are presented as follows:

- **Owners control proactive measures and funding priorities, and they are the most influential decision-makers**

Dam owners are the primary decision-makers for maintenance, and engineers challenge them to ensure sufficient funding and risk management. One of the interviewees explicitly noted that maintenance decisions are largely controlled by owners, and engineers are often excluded from important discussions: *"The owner usually takes the lead on that. And a lot of times they would rather do that themselves. So, it is not something that we shy away from, but we are not often invited to the table."* This reinforces the fact that engineers are sometimes excluded from key maintenance discussions, even when their expertise is critical. Another interviewee pointed out that short-term financial decisions often drive maintenance choices rather than long-term sustainability: *"Sometimes it depends on the financing, the funding. But in the ideal world, it is to be engaged from the concept through long-term operation and maintenance. Often it can be driven by short-term financial decisions rather than a longer-term perspective."* This acknowledges the financial tension between engineers and owners regarding maintenance investments. In another interview, one of the engineers emphasized that public safety is the primary concern for engineers, but owners have a strong influence on whether safety measures are prioritized: *"Our primary obligation is public safety, which is just nice. I like that. I mean, it is ideal when your client also places the same value on public safety, and typically, they do. Most people do, so it is an easy value to support."* This quote suggests that engineers may need to challenge their perceptions when owners do not prioritize safety. The following quotes from two different interviewees provide further insight into the influential role of owners in decision-making, which ultimately impacts maintenance practices.

"We need to get all the perspectives at the table, but at the end of the day, the client decides. They are the ones setting priorities, and we work within that framework."

"The owner usually takes the lead in funding decisions. Engineers provide assessments, but we don't always have the final say."

- **Communication between engineers and owners shapes maintenance budgets, and engineers struggle to convince owners about risk and maintenance needs**

One of the interviewees mentioned that maintenance is often undervalued, despite being critical: *"You can use the best methods to build the best bridge, but if you do not maintain it, it would not work. Maintenance is not flashy. It is difficult to justify spending money on something that is not visible until it fails."* This indicates that engineers must actively advocate for maintenance funding because owners may deprioritize it. On the other hand, they described the bureaucratic and financial challenges engineers face when pushing for higher safety standards and this shows the systemic issue where engineers are forced to negotiate for proper funding; for instance, one participant said: *"The feasibility criteria have a lower standard than the final design. So, when the project is authorized, it automatically has a lower budget estimate. Then they bring in the designer and say, this has been authorized, but we're not giving you more money to meet the higher standard"*. Additionally, engineers confirmed that budget constraints, not technical capabilities, are the main limiting factor in engineering projects: *"The limiting factor is really the budget rather than the tools. You can have the best design, but if the funding isn't there, it won't be implemented properly"*. Several interviewees expressed concerns about how political dynamics influence risk perception and funding stability in dam and infrastructure projects. Their insights explain how political shifts, regulatory inconsistencies, and funding uncertainties create volatility in risk perception and decision-making processes. However, communication between engineers and owners can shift the maintenance budget:

"For private entities, their engagement with the community is done through the permit process. It is kind of outside the direct intervention of a designer or an engineer. Some engineers get questions, but not all communities have formal engagement structures in place."

"Sometimes you just have to push through even when you see inefficiencies or ethical dilemmas in the system. We try to make the best case for safety, but it is a negotiation."

- **Risk perception and budget allocation for maintenance**

The following quotes from two different engineers provide evidence of the importance of risk perception in budget allocation:

"Risk is the factor of three things: how likely are you to see the event, how the infrastructure will perform in the face of that event, and what the consequences are if it doesn't. The consequences piece—people, property, environment—is where we have to engage people because there are trade-offs."

"Public safety is the foundation of civil engineering. But without clear risk communication, decision-makers may underfund critical maintenance." Ultimately, allocating a budget is less a technical exercise and more a process of negotiation, shaped by how risk is framed and understood. Clear, concrete communication from engineers—linking risks to dire outcomes like loss of life, property destruction, and ecological harm—effectively motivates investment in maintenance. However, if these risks remain abstract or are poorly conveyed, funding is typically postponed until a catastrophic failure makes the need indisputably clear.

- **Engineers are becoming more risk-averse after disasters, leading to code changes**

After each disaster, even engineers' risk perception changes, and they become more risk-averse in their work. This trend has been observed over time, and engineers acknowledge it as follows:

"After Katrina, it changed everything. Suddenly, flood protection had to be designed to a new standard. Before that, the risk just was not seen the same way."

"Ethics change over time. Society does not make decisions today like it did 50 years ago. The primary ethic at the time was to get water away from cities as fast as possible, but environmentally, that was a disaster. Engineers have to learn and adapt to society's changing ethics."

Additionally, awareness of risk rises and falls over time, often leading to neglect of proactive measures until disaster forces action. People are aware of risks and the need for maintenance, but this knowledge does not always translate into action due to financial and political constraints, as explained in the quote below:

"There is a gap between what we know should be done and what actually gets done. Money is always a factor, and unless a disaster occurs, getting funding for long-term risk management is hard."

"Public safety is the foundation of civil engineering. But without clear risk communication, decision-makers may underfund critical maintenance."

- **Political cycles and regulatory instability affect risk perception**

Weak regulations and poor decision-making by organizations can lead to serious consequences (Schweiger, 2018). One expert mentioned that political leadership changes can shut down large-scale infrastructure projects on short notice, causing significant uncertainty in long-term planning. This reflects how risk perception among engineers and decision-makers changes due to inconsistent political priorities: *"There is the political space. Again, with these changes… political leadership shifts as well. That can really shut down very large projects on pretty quick timelines. And the regulatory space also changes, which creates uncertainty"*. This quote demonstrates the challenge of aligning long-term maintenance and risk management strategies with short-term political cycles. The result is a gradual erosion of resilience, where temporary political decisions have lasting consequences on structures intended to endure for generations. As a result, engineers struggle to plan for infrastructure resilience when political leadership and regulatory priorities are unpredictable.

- **Political influence leads to uncertainty in long-term risk planning**

Regarding this theme, some engineers discussed how political factors influence risk assessment frameworks, making it difficult to apply consistent long-term strategies: *"What is your water level you are designing to? What is the wave energy you're designing to? That pretty much decides every other design criterion. But future conditions, regulations, and political decisions create huge uncertainties in defining those parameters."* Political affiliation can potentially change the direction of infrastructure design parameters, making it difficult for engineers to apply uniform risk-based standards.

- **Political influence impacts climate risk and regulatory approaches**

One expert noted how climate change regulations and adaptation strategies vary based on political leadership, leading to inconsistencies in funding and risk perception: *"Florida is fairly less conservative. but different jurisdictions have different approaches. Some are aggressively incorporating climate change risk into their infrastructure plans, while others ignore it. So, yes, political leanings are a driver."* The politicization of climate change results in uneven regulation enforcement, which affects the risk perception of engineers and infrastructure planners. This inconsistency is especially problematic given that climate risks evolve over decades, while political cycles operate on much shorter timescales. As a result, long-term adaptation strategies are frequently interrupted or reversed, leaving infrastructure projects vulnerable to shifting priorities

2.3 First-hand data from a U.S.-based questionnaire

In order to understand the factors influencing the risk perception and decision-making of engineers, we conducted a survey to collect data from experienced engineers who specialize in dams and coastal infrastructure (Pourmatin et al., 2025). This survey examined engineers' personal and work-related risk perception, their attitudes toward incorporating climate change and environmental justice into design, their views on the efficacy of education and standards, and the overall industry culture. The majority of respondents were male, while only 18 percent were female, and most held a master's degree. Most respondents confirmed that their education had not prepared them well, and this factor can influence their personal attitudes when they are making decisions for designing and choosing materials for infrastructure. This outcome identifies a significant gap in engineering education. Curricula for engineering place substantial emphasis on technical design and analysis but provide less guidance on communicating risk, economic justification of maintenance, and politics. Addressing the education gap is essential for achieving an engineering culture well equipped to advocate the case for long-term resilience. These survey findings not only highlight a gap in technical training but also provide behavioral inputs for the system dynamics framework developed in this study. The variability in engineers' attitudes toward risk, climate change, and communication directly shapes feedback loops in maintenance decision-making, particularly those involving risk perception, funding advocacy, and owner–engineer negotiations.

2.4 Hypothesis definition

While multiple factors influence dam maintenance and resilience (e.g., regulatory frameworks, institutional priorities), this study focuses on the interaction between risk perception, decision-making, and financial allocation for maintenance (Mohebbi et al., 2020). These factors emerged as the notable themes from the analysis of interviews and survey responses. Based on this analysis, we hypothesize that the risk perception of engineers and dam owners, along with the availability of financial resources, plays a critical role in determining maintenance funding and long-term infrastructure resilience. According to our dynamic hypothesis, engineers' risk perception influences their advocacy for maintenance funding, which in turn affects the dam owners' budget allocation decisions. When owners perceive maintenance costs as excessive or immediate risks as low, funding allocations may be insufficient, leading to gradual deterioration of dam conditions. As dams transition from good to fair and eventually poor condition, the likelihood of failure increases, further reinforcing engineers' perception of risk. Following a disaster event or major failure, risk perception rises significantly, leading to stricter regulations and increased financial allocations for maintenance. However, over time, as the absence of failures reduces perceived urgency, awareness declines, potentially leading to relaxed maintenance efforts and funding reductions. This cycle highlights the systemic challenge of sustaining proactive maintenance policies without reliance on disaster-driven funding adjustments.

2.5 Causal loop and stock flow framework

The causal loop diagram (CLD) presented in this study includes dynamics that shape dam maintenance, risk perception, and regulatory responses to infrastructure deterioration. This model focuses on the interactions between dam owners' budget allocation, engineers' risk perception, and the physical deterioration of dams, revealing how these relations in closed loops drive decision-making and long-term resilience. Figure 1 demonstrates the CLD of the main factors discussed in this paper.

- Maintenance budget, perceived costs, and deterioration

Dam deterioration is the core of the presented system, and the assumption is that deterioration progresses based on the level of maintenance investment. The balancing loop demonstrates that higher maintenance budgets lead to increased maintenance activities, which in turn ameliorate the rate of dam deterioration. However, this loop also includes a reinforcing mechanism, which explains that the perceived cost of maintenance affects how much budget is allocated. This structure represents a common pitfall in infrastructure management, where decision-makers often perceive maintenance costs as excessive, especially in the absence of an immediate failure risk (McAlister et al., 2024). As a result, funding is frequently reduced until visible signs of deterioration force urgent interventions, which are less effective than proactive maintenance. This short-term cost-saving mindset accelerates long-term infrastructure decline, creating a vicious cycle of delayed action and escalating risk.

- Engineers’ risk perception and the influence of disasters

Risk perception and communication are essential ways to influence the managerial decisions and actions taken by stakeholders (Zhang et al., 2017). A crucial reinforcing feedback loop captures how engineers’ risk perception influences maintenance investments. As dams deteriorate, the probability of failure events increases. If a disaster occurs, engineers' perception of risk dramatically rises, leading to stricter regulations and a corresponding increase in maintenance funding. This response cycle underscores a well-documented phenomenon in infrastructure governance—reactive rather than proactive decision-making. However, this loop also contains a delayed response mechanism. As time passes without further incidents, risk perception gradually declines, leading to a relaxation of regulations and reduced budget allocations, eventually restarting the cycle of underinvestment. This regulatory decay effect reflects historical patterns seen in dam safety and broader infrastructure management, where funding and regulatory communications peak after disasters but fade as perceived risk diminishes over time.

- The urgency-maintenance trade-off and systemic delays

Another significant balancing loop highlights how urgency affects maintenance decisions. When dam deterioration reaches a critical level, urgent maintenance becomes necessary. However, urgent maintenance is more expensive and less efficient than routine upkeep, exacerbating financial constraints. Because urgent maintenance is often implemented under crisis conditions, it diverts funds from preventative maintenance efforts, perpetuating a cycle where resources are allocated only when failure risk is imminent. This loop shows real-world infrastructure management challenges, where maintenance is deferred until political or public pressure forces action, often at a higher cost and with fewer long-term benefits.

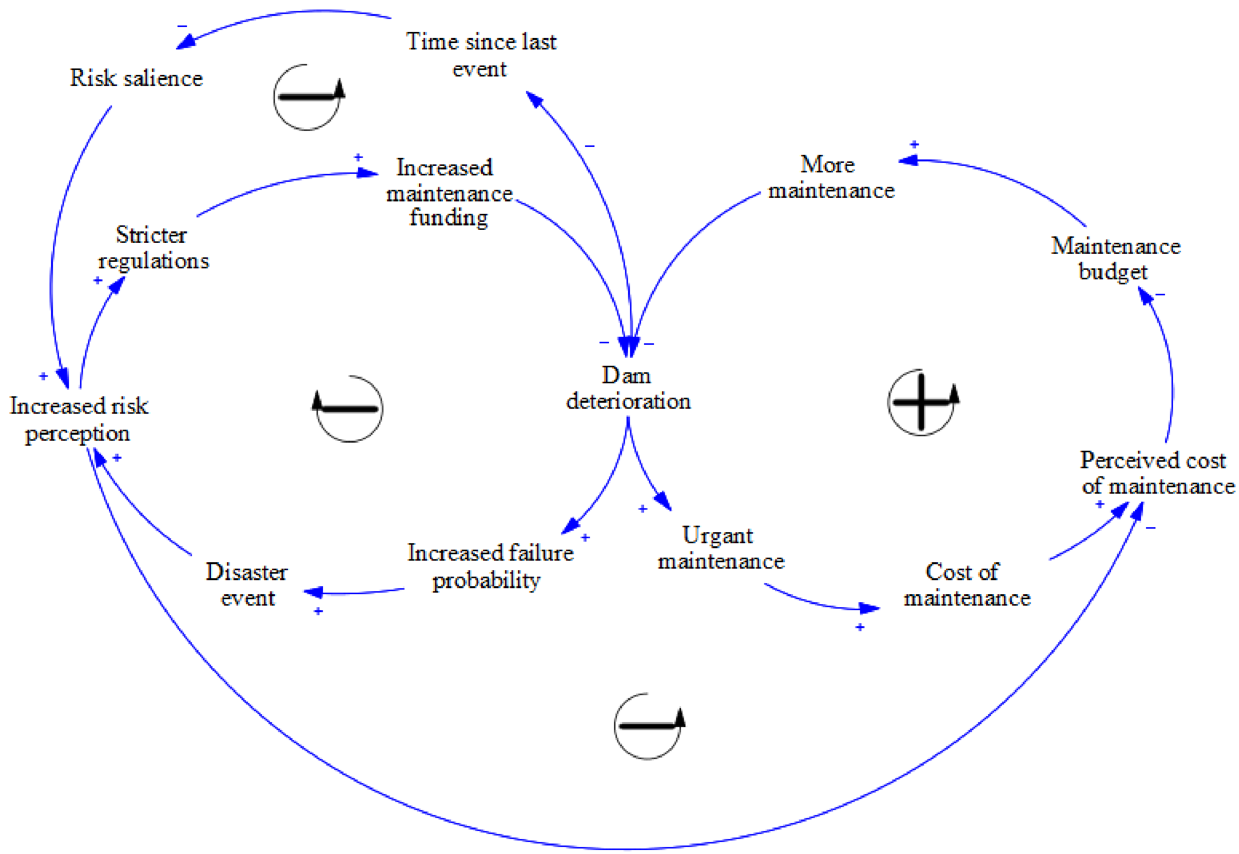

Figure 1. Feedback loops of the main variables

Figure 2 represents the stock flow diagram of the model proposed in this study. We used interview data to start the loops, as shown in Figure 1. However, Figure 2 incorporates additional insights from various sources, including literature and the research team's expertise, as well as the interviews. When owners perceive maintenance costs as high, they may redirect budget allocation to other priorities, avoiding maintenance spending. This decision-making behavior is commonly observed in infrastructure management, where short-term financial constraints lead to deferral of long-term maintenance investments. In reality, maintenance costs tend to increase over time if we do not address them early, and inadequate maintenance will be reinforced (Smith & Hawkins, 2004). On the other hand, higher risk perception after disasters increases pressure on policymakers to enforce stricter regulations. Historical examples show that catastrophic failures (e.g., dam collapses, floods) trigger regulatory reforms. Regulations do not change directly due to risk perception alone—they also depend on political will, economic feasibility, and lobbying forces. We have considered an intermediate variable like "Policy response to risk perception" to account for the fact that risk awareness does not automatically translate into regulatory action. This ensures that policy inertia and competing interests are considered in regulatory shifts. Table 1 describes the meaning of all variables used in the stock-flow diagram (Figure 1) in this paper.

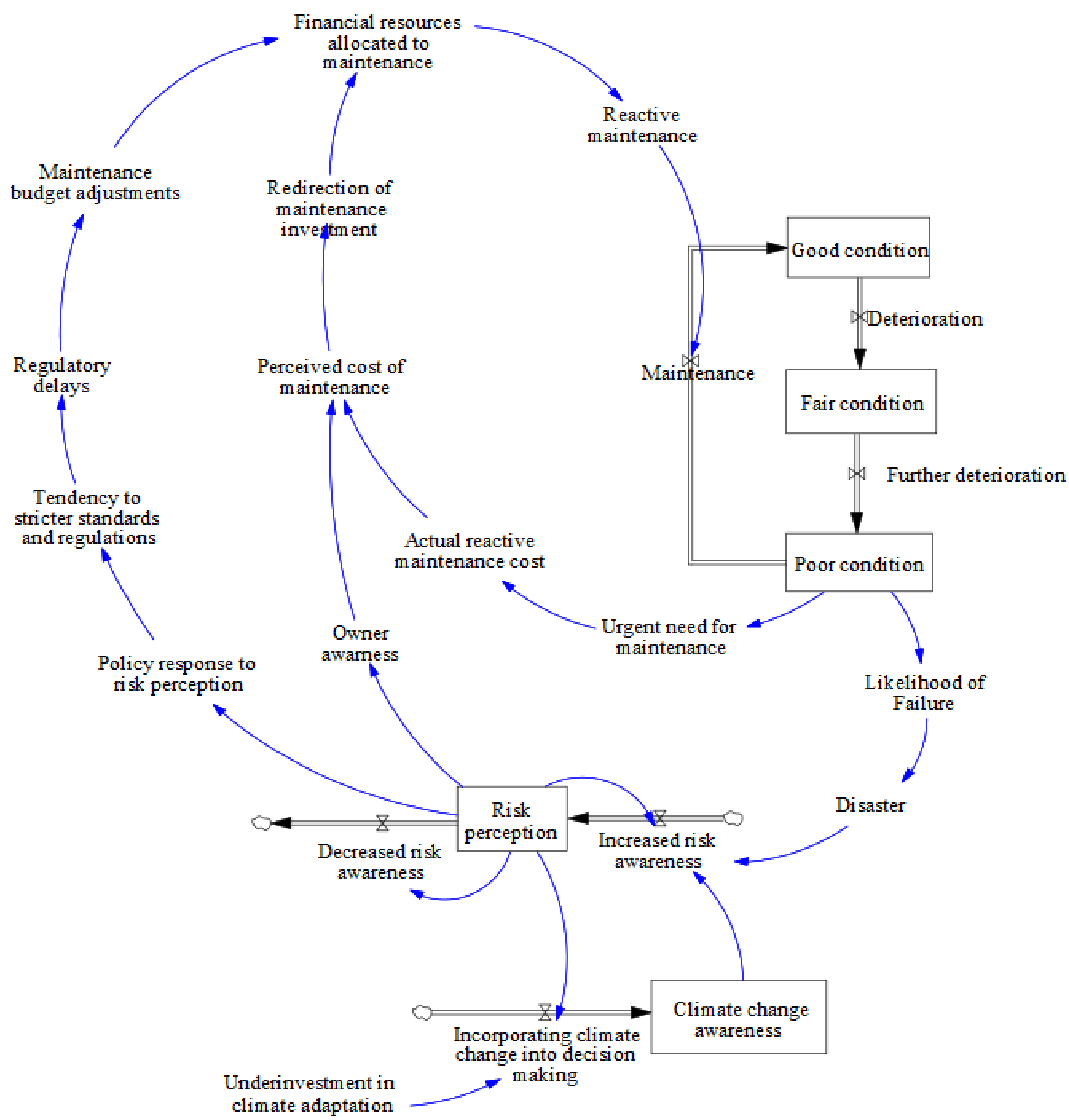

Figure 2. Proposed stock-flow diagram to manage risk perception and protection activities.

Table 1. Description of variables used in the stock-flow diagram

Variable Name	**Definition**
Financial resources allocated to maintenance	The budget or funds specifically dedicated to proactive maintenance to sustain infrastructure resilience.
Reactive maintenance	Maintenance actions taken only after failures occur, rather than preventive maintenance.
Maintenance	Regular and planned interventions to keep infrastructure in good working condition.

Good condition	The ideal state of the dam infrastructure, where deterioration is minimal, and functionality is optimal.
Fair condition	A mid-level state where the infrastructure is still functional but requires increased maintenance to prevent further degradation.
Poor condition	A severely deteriorated state of infrastructure, where failure risk is significantly increased.
Deterioration	The gradual decline of dam conditions over time due to wear, environmental stress, and lack of maintenance.
Further deterioration	The worsening of infrastructure beyond the 'fair condition' state, making failure more likely.
Likelihood Probability (the term we used mostly) of failure	The probability that the dam will experience significant structural failure due to lack of maintenance.
Urgent need for maintenance	A condition where infrastructure deterioration has reached a point requiring immediate intervention.
Disaster	A catastrophic failure of the dam (e.g., collapse, flooding) that triggers emergency response and funding.
Risk perception	The awareness and assessment of infrastructure-related risks by engineers, policymakers, and stakeholders.
Increased risk awareness	A rise in understanding of risks, leading to stronger policy responses, funding, and maintenance decisions.
Decreased risk awareness	A decline in risk perception, which can result in complacency, funding cuts, and weaker regulations.
Climate change awareness	Understanding of how climate change influences dam resilience and maintenance needs.
Incorporating climate change into decision making	The extent to which climate change considerations are integrated into infrastructure planning and maintenance policies.
Underinvestment in climate adaptation	Insufficient financial and institutional investment in climate adaptation measures, increasing vulnerability.
Owner awareness	The level of understanding and concern among infrastructure owners regarding maintenance needs.
Perceived cost of maintenance	How decision-makers perceive the cost of maintenance, which influences budget allocation.
Redirection of maintenance investment	The shift of budget away from proactive maintenance to other expenditures.
Policy response to risk perception	Governmental or organizational reactions to increased risk perception, often leading to regulatory changes.
Tendency to stricter standards and regulations	A tendency for regulatory frameworks to become stricter in response to failures and perceived risks.
Regulatory delays	Delays in implementing regulatory changes, affecting maintenance funding cycles.
Maintenance budget adjustments	Adjustments made to maintenance funding in response to regulations or financial constraints.
Actual reactive maintenance cost	The actual cost incurred when performing reactive maintenance after failures occur.

3. Policy implications and improvement strategies

In this study, we present policy-based refinements to the stock-flow model, which will enhance its applicability to real-world decision-making. Key variables are clarified to elaborate on the proposed policies and suggest refinements with additional feedback loops.

1. Continuing education through risk awareness workshops for engineers

Risk perception is closely linked to disaster salience, e.g., after recent exposure to a disaster, individuals tend to feel more risk-averse. Thus, holding regular workshops for engineers as part of continuing education requirements to strengthen their risk awareness could directly impact their perception of dam safety, failure risks, and maintenance needs. These workshops should be multi-disciplinary, involving not just engineers but also project owners, emergency managers, and local policymakers. The goal is to create a shared understanding of risk, not just to train engineers.

2. Institutionalized risk assessment and multi-year funding cycles

Engineers with lower tolerance for risk (e.g. a higher level of risk aversion) are more likely to advocate for proper maintenance funding and communicate risks more effectively to policymakers and dam owners. This suggested intervention would help mitigate the common cycle of disaster salience fading over time, which would help ensure long-term regulatory commitment. If workshops provide continuous knowledge transfer, this can help prevent risk salience from declining after disasters fade from memory. One of the main challenges in securing long-term infrastructure funding for dam maintenance is that resource allocation for climate change-related projects is often dependent on the current political climate. Several experts in the interviews noted that funding for resilience projects fluctuates based on political cycles, regulatory uncertainty, and shifting priorities among decision-makers. This uncertainty often results in inconsistent maintenance efforts, leading to infrastructure vulnerability and increased disaster risks. For instance, one of the interviewees mentioned that large-scale projects often get delayed or even discontinued due to political influences rather than technical feasibility. Another expert pointed out that some flood mitigation projects gain attention only when certain political leaders advocate for them, whereas others face neglect due to partisan biases. Thus, depoliticizing climate change mitigation and adaptation measures in infrastructure decision-making is critical for ensuring consistent, data-driven funding allocations and maintenance policies that are unaffected by political shifts. However, depoliticization is not straightforward; rather, it should focus on creating institutional safeguards that insulate technical decisions from short-term political influences while maintaining democratic accountability.

Institutionalized risk assessment policy refers to a formalized, regulatory process in which risk is continuously assessed and incorporated into long-term infrastructure planning. Unlike short-term risk evaluations, institutionalized assessments ensure that maintenance funding is systematically linked to risk levels rather than political cycles. In practice, this can include regulatory structures such as permit allowances, tax abatements, and zoning measures to encourage proactive maintenance. Formulating and implementing such a policy could help ensure stable, long-term financial commitments to infrastructure safety, which multi-year funding cycles also reduce overall life-cycle costs by avoiding the higher expenses associated with emergency interventions.

Predictable allocations allow for scheduled inspections, preventive reinforcements, and gradual upgrades that are significantly less costly than post-failure repairs. This can shift funding from reactive repairs toward proactive maintenance strategies. Moreover, institutionalized risk assessments provide co-benefits across sectors by aligning dam safety with flood risk management, water supply reliability, and energy security. This integrated perspective strengthens the case for consistent funding, as it highlights the systemic consequences of underinvestment

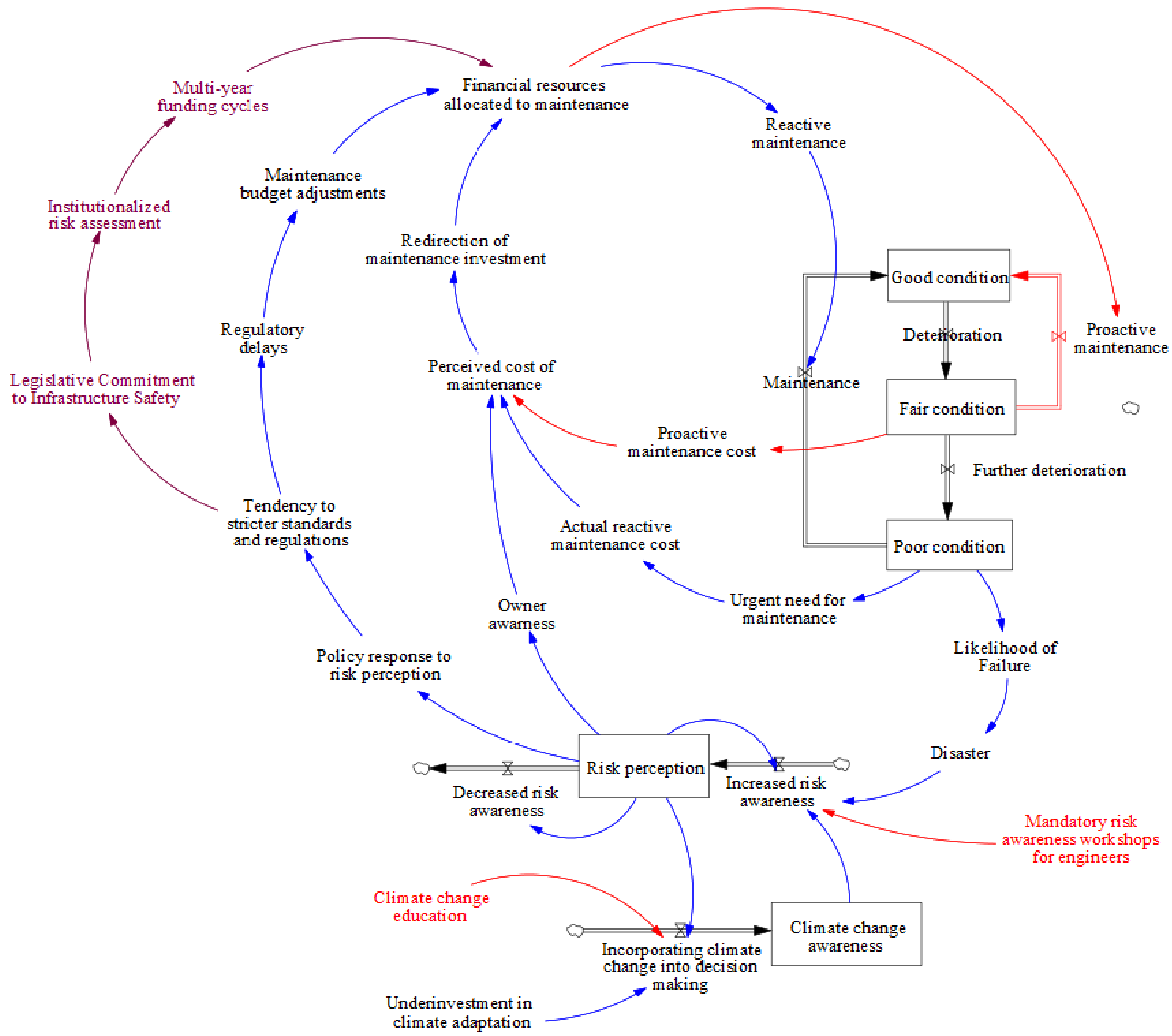

Figure 3. Refinement loops and policies

4. Conclusion

This study proposes that dam safety is not just a technical issue, but it is also a function of human decision-making. While engineers play a key role in assessing risks and proposing solutions, the final decisions regarding maintenance, protections measures, and funding are made by dam owners and policymakers, whose choices are shaped by financial pressures, political cycles, and regulatory uncertainties. Using a system dynamics approach, this research explores the causal relationships that drive both proactive and reactive maintenance decisions. The findings show that short-term financial priorities, shifting political agendas, and inconsistent regulations often result in a reactive approach, where necessary safety improvements are only made after failures occur. To break this cycle, it is essential to establish long-term risk assessments, ensure stable maintenance funding, and improve communication between engineers and decision-makers. Without addressing the financial and political barriers that influence maintenance decisions, dam safety efforts will continue to focus on fixing problems rather than preventing them. A major challenge identified in this study is the gap between technical risk assessments and actual decision-making. Engineers understand the risks of dam deterioration, but they often struggle to secure the funding needed for proper maintenance and protection measures. Dam owners, on the other hand, prioritize short-term cost savings over long-term resilience due to financial and political constraints. This leads to a cycle where maintenance is delayed until a crisis forces immediate action. This approach will result in higher costs and increased risks. To improve dam safety, infrastructure management must shift from reactive to proactive maintenance strategies. In addition, climate change and the increasing frequency of extreme events further amplify the urgency of shifting toward proactive maintenance. Long-lived infrastructure such as dams must be managed with forward-looking strategies that account for uncertain future conditions rather than relying solely on past performance. This requires a change in how risk perception and financial planning are integrated into decision-making. Continuing education for engineers, stable funding structures, and institutionalized risk assessments can help bridge this gap. By adopting these strategies, decision-makers can move toward a more sustainable, risk-aware, and resilient approach to dam upgrades, ensuring long-term safety and stability.

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