frontiers in Water

TYPE Original Research
PUBLISHED 30 March 2026
DOI 10.3389/frwa.2026.1748569

OPEN ACCESS

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RECEIVED 18 November 2025
REVISED 19 February 2026
ACCEPTED 27 February 2026
PUBLISHED 30 March 2026

CITATION
Ishiwatari M, Fukuwatari T and Kawasaki A (2026) Short-term optimization, long-term vulnerability: system-level economics of flood protection and urban development in the Shinanogawa River.
*Front. Water* 8:1748569.
doi: 10.3389/frwa.2026.1748569

# Short-term optimization, long-term vulnerability: system-level economics of flood protection and urban development in the Shinanogawa River

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Flood protection infrastructure can paradoxically increase vulnerability through the 'levee effect' or the 'safe development paradox'. In some cases, protection can reduce the perceived risk of flooding, leading to the intensive development of floodplains. This may necessitate additional investment, as short-term rational optimization can create long-term vulnerabilities through path-dependent processes that are difficult to reverse. However, the empirical evidence is limited. This study uses the Shinanogawa River Basin in Japan as a case study to examine this feedback cycle and the dynamics of the coupled human–water system over the centuries. The study reconstructs economic analyses to provide a systematic, long-term, river-basin-wide examination. This retrospective analysis aims to extract lessons that can be applied to current and future flood protection and development planning in the context of climate change and evolving social values, rather than criticizing past decisions in hindsight. The completion of the Okozu Diversion Channel in 1924 reduced flood risk in Nigata City, enabling river reclamation in the 1930s and 1940s. While this project contributed to the development of Nigata City, it also narrowed the river, reducing its flood capacity. Although these reclamation projects appeared profitable at a project level, they created hidden liabilities, necessitating the construction of the Sekiya Diversion Channel in 1972. Together, these interventions resulted in a net system loss of 12 trillion JPY, or 80 billion USD, at maximum. System-level analysis reveals reclamation created a hidden liability requiring compensatory infrastructure costing 365 billion JPY, or 2.4 billion USD (2015 prices, 4% discount rate). This analysis demonstrates how conventional project-level cost-benefit analysis can mask system-wide implications and liabilities. The study traced interventions and social responses, revealing that the temporal mismatch between human decision-making timeframes (years to decades) and the frequency of hydrological events (decades to centuries) was the driving force behind this dynamic. Flood management strategies must consider the long-term by incorporating the uncertainty caused by climate change and the changing environmental and cultural values of water.

KEYWORDS

**climate change adaptation, flood protection, levee effect, path dependency, safe development paradox, Shinanogawa river basin**

# 1 Introduction

## 1.1 Problem statement and motivation

Flood protection strategies must consider the long term in a changing climate, as hydrological changes will persist for decades or even centuries (Kundzewicz et al., 2010; Ishiwatari et al., 2023; Granata and Di Nunno, 2025). It is essential to understand how decisions made by previous generations regarding infrastructure development affect vulnerability in order to adapt to changing climates and societies. The timing of decisions about climate change adaptation does not align with the timing of hydrological extremes caused by climate change.

Human societies and water systems are deeply coupled, characterized by dynamic feedback loops, and are not separate entities (Di Baldassarre et al., 2015; Ding et al., 2023). In some cases, flood protection infrastructure can actually increase vulnerability. While levees, dams and diversions can reduce routine flooding, they can also create a false sense of security that exacerbates the problem. Investments in flood protection could encourage intensive development in floodplains. These development activities could reduce natural flood capacity and create latent vulnerability—a hidden liability that may not actualize for decades until rare extreme events occur or until compensatory infrastructure becomes necessary. While socio-hydrological research documents feedback loops qualitatively (Di Baldassarre et al., 2015; Yu et al., 2022), few studies quantify system-level economic implications of sequential interventions over century timescales.

## 1.2 Conceptual background: conventional CBA in flood protection and its limitations

Conventional cost benefit analysis (CBA) frameworks—the dominant tool for evaluating flood protection investments globally—typically evaluate individual projects in isolation, focusing on direct costs and immediate benefits within planning horizons. Standard CBA procedures evaluate flood protection projects by comparing construction, operational and maintenance costs with monetized benefits over a planning horizon of 20-50 years. Projects with benefit-cost ratios exceeding 1.0 are considered economically justifiable. These benefits usually include preventing structural damage to buildings and infrastructure, avoiding business interruption costs, and reducing casualties (MLIT, 2022b).

Social discount rates represent the rate at which future costs and benefits are converted into present value. They reflect factors such as time preference, the opportunity cost of capital and risk. The social discount rate is different in each country because, according to standard economic analysis, it is connected to the country's long-term growth outlook. Future benefits and costs should be evaluated based on their marginal contribution to welfare, which decreases as growth rates increase and future project beneficiaries become wealthier. Generally, the higher the growth outlook, the higher the discount rate tends to be (World Bank, 2016).

When applied to flood protection in coupled human-water systems, conventional CBA frameworks suffer from systematic limitations that can lead to misleading evaluations: First, standard evaluation periods of 20-50 years may be too short to capture rare hydrological extremes or delayed consequences of infrastructure decisions. Major floods may have return periods exceeding typical analysis horizons (e.g., 100 year, 200 year events), making tail risks invisible to conventional assessment. This temporal limitation becomes particularly problematic when infrastructure decisions are effectively irreversible.

Second, evaluating each intervention independently fails to account for system-wide interactions and compound effects. When one project's benefits depend on or are negated by subsequent projects, isolated analysis produces misleading results. Conventional CBA cannot capture how an "economically justified" project might create hidden liabilities requiring future compensatory investments that exceed the original project's value.

Third, most CBA frameworks assume risk perception remains constant or adjusts rationally to actual risk levels. They do not model how protection infrastructure fundamentally alters perceived risk and enables behavioral changes—such as floodplain development—that increase system-wide exposure. This behavioral feedback represents a critical gap in standard evaluation methodology.

Fourth, conventional approaches typically cannot account for hidden liabilities—vulnerabilities created by projects that only become apparent decades later. When protection enables development that reduces natural flood capacity, this latent vulnerability does not appear in project-level evaluation, yet may require expensive compensatory infrastructure in the future.

## 1.3 Research gaps and questions

This paper aims to propose long-term flood protection strategies in the face of uncertainties caused by climate and societal changes. Research questions cover: (i) how feedback loops shape coupled human-water system evolution, (ii) what true system-level economic implications are when analyzed holistically, and (iii) what transferable insights apply to contemporary flood management.

Rather than criticizing past decisions in hindsight, this retrospective analysis extracts systematic lessons to inform current and future flood protection and development plans. Several countries, particularly developing ones, are currently engaged in large-scale flood protection and urban development projects (Merz et al., 2021; Ishiwatari and Sasaki, 2024). This study contributes to the development of flood protection strategies that account for uncertainty, changes in water value, and societal changes.

## 1.4 Case selection and justification

This study analyzes the Shinanogawa River Basin in Japan. As Japan's longest river at 367 km, the Shinanogawa represents a system of exceptional complexity and historical significance. The river's challenging geography—characterized by complex terrain, steep gradients in upper reaches transitioning to the expansive low-lying Echigo Plain—has generated centuries of flood management challenges requiring sustained engineering intervention.

The Shinanogawa case is uniquely suited for addressing the research gaps identified above for several conceptual and empirical reasons. First, the Okozu Diversion Channel (completed in 1924) represents one of Japan's pioneering modern flood protection works—a symbolic achievement of early twentieth century hydraulic engineering that fundamentally reorganized human-water relationships in the basin. This major intervention provides a clear "system disturbance" initiating observable feedback cycles.

Second, the sequence from the Okozu Diversion Channel (completed in 1924) through river reclamation (1930s-1940s) to the Sekiya Diversion Channel (completed in 1972) provides a cycle with sufficient temporal separation (nearly 50 years) to observe long-term consequences. This temporal span is essential for detecting feedback dynamics that conventional planning horizons miss.

Third, Japan's meticulous record-keeping provides century-long historical records, including detailed project reports, economic analyses conducted, flood event records, and land use changes. This enables reconstruction of decision-making processes and quantitative analysis that would be impossible in most other contexts. The case clearly manifests the protection-development-exposure cycle with quantifiable outcomes. The availability of detailed economic data for both implemented projects and abandoned plans (1963 reclamation proposal) enables counterfactual analysis. This allows systematic comparison between actual outcomes and alternative trajectories, strengthening causal inference about system-level effects.

Fourth, while the specific historical and cultural context is Japanese, the fundamental dynamics observed are not unique to Japan. Temporal mismatch between decision horizons and hydrological extremes, institutional pressure for visible development progress, evolving social values regarding water environments—are not unique to mid-twentieth century Japan. Rather, they represent general features of flood risk management decision-making that remain relevant today, particularly for developing regions where climate adaptation and flood management strategies are currently being designed.

## 1.5 Paper structure

Section 2 reviews relevant literature on socio-hydrological frameworks and economic evaluation approaches. Section 3 describes the case context and methodology. Section 4 presents the retrospective analysis of sequential interventions. Section 5 provides analytical interpretation contrasting project-level and system-level economic evaluation. Section 6 synthesizes broader implications and transferable lessons. Section 7 provides lessons learned, and section 8 concludes.

# 2 Socio-hydrological framework for understanding flood-development interactions

This section reviews recent literature that examines the socio-hydrological frameworks of flood and development and articulates how conventional CBA practices often fail to capture system-level dynamics. There is limited literature analyzing the interactions this study focuses on.

## 2.1 Coupled human-water systems

Recent advances in socio-hydrology emphasize the need to recognize the interdependence between society and water systems, treating them as coupled human-water systems rather than separate domains (Di Baldassarre et al., 2015; Yu et al., 2022). This framework revealed how human intervention in hydrological systems triggers feedback.

Urbanization, the environment, and flood risks form a tightly coupled system with multiple feedback loops. Various studies have demonstrated that urbanization deteriorates water cycles and increases flood damage by modifying land cover, drainage patterns, and settlement distribution (Wang et al., 2022; Rentschler et al., 2023). In response, societies have constructed structural measures, such as levees and dams, to mitigate flood damage.

Key theoretical concepts in socio-hydrology include: (i) bidirectional causality between human actions and hydrological responses; (ii) time-lagged feedback where consequences of interventions may not manifest for decades; (iii) emergent system properties that cannot be predicted from analyzing components in isolation. Methodologically, socio-hydrological studies have primarily employed qualitative case analysis, system dynamics modeling, and agent-based simulation. Empirical findings consistently document feedback loops but rarely quantify their long-term economic implications.

## 2.2 Positive and negative feedback in flood protection

Urban flood-protection systems can generate positive feedback by promoting healthy urban development through rainwater management (Lourenço et al., 2020). Doeffinger and Rubinyi (2023) identified four categories of secondary economic benefits, such as increased property values; societal benefits, such as recreational opportunities; infrastructure benefits, such as new transportation routes; and environmental benefits, such as reduced carbon emissions. Investments in flood protection can promote socio-economic development and reduce poverty (Okuda and Kawasaki, 2022).

However, structural flood protection creates critical negative feedback known as the "levee effect" or "safe development paradox." Although levees prevent routine flooding, they create a false sense of security that encourages intensified development in floodplains without adequate preparation for rare but catastrophic events (Stevens et al., 2010; Di Baldassarre et al., 2015; Ding et al., 2023; Junger and Seher, 2024). This paradox represents fundamental socio-hydrological feedback—physical protection reduces perceived risk as a social response, which increases exposure to physical vulnerability, ultimately amplifying consequences when protection fails.

Burby (2006) demonstrated this dynamic in New Orleans, where federal flood protection projects increased catastrophic flood risk by enabling extensive development in vulnerable areas, setting the stage for Hurricane Katrina's devastation. Burby's analysis was primarily qualitative institutional analysis. While it compellingly demonstrated policy failure, it did not reconstruct detailed economic accounting showing how individual project-level decisions aggregated to system-level vulnerability. This case illustrates how the temporal mismatch between human decision-making horizons and hydrological event frequencies can lead to unsustainable trajectories in coupled human-water systems.

Empirical documentation of the levee effect spans multiple contexts. Di Baldassarre et al. (2015) employed system dynamics modeling to demonstrate feedback mechanisms conceptually but did not quantify cumulative economic impacts. Ding et al. (2023) analyzed Chinese floodplain development using spatial analysis and found development concentration behind levees, but their study lacked long-term economic accounting. These methodological approaches—while valuable for documenting patterns—cannot capture century scale system-level costs and benefits.

## 2.3 Research contribution

The research gap lies at the intersection of these literatures. Socio-hydrological research tends to document feedback qualitatively rather than quantifying the cumulative economic effects. CBA methodology evaluates individual interventions but lacks frameworks for system-level accounting across interdependent projects.

A century-scale, system-level analysis has been rarely conducted. Such analyses require large amounts of data on century-long economic and hydrological records, which are available in few contexts. Also, the methodology is complex: linking sequential projects requires the reconstruction of counterfactual scenarios and attribution of causality across decades.

This study uses system-level economic accounting to reconstruct sequential interventions as a coupled system. This approach addresses the fundamental limitations of conventional CBA and requires methodological modifications to economic analysis, including:

(i) The explicit modeling of interdependencies between sequential projects.

(ii) Accounting for capacity changes and hidden liabilities.

(iii) Incorporating behavioral feedback, i.e., changes in risk perception that enable development; and

(iv) Valuing preserved system resilience.

The modified approach can quantify how rational short-term project decisions collectively produce negative net system value over centennial timescales. This advances socio-hydrological economics beyond documenting that feedback loops create vulnerability to quantifying how much they cost.

# 3 Case and methods

## 3.1 Flood disaster and flood protection works in the Shinanogawa river

The Shinanogawa River, Japan's longest river at 367 km, drains a basin of 11,900 km$^2$, and is home to 2.83 million inhabitants (Figure 1). The river poses disaster risks, with 1.74 million people and assets worth 37 trillion JPY, 250 billion USD, located in flood-prone areas (MLIT, 2022a). The river's downstream reaches traverse the Echigo Plain, where they form an intricate hydrological network with tributary rivers and lakes, creating complex flood management challenges. The Echigo Plain, located in Nigata Prefecture, is one of Japan's most productive rice-growing regions. This agricultural landscape extends approximately 100 km north-south and 10-25 km east-west and encompasses approximately 2,070 km$^2$.

The geological history of the plain explains why such extensive intervention is necessary. Formed by sediment deposition from the Shinanogawa and Aganogawa Rivers over approximately 10,000 years, the area originally consisted of low-lying wetlands prone to frequent inundation. Coastal sand dunes further complicate drainage patterns, effectively trapping water within the plain and rendering the land unsuitable for stable agricultural use (Sato et al., 2006). These natural conditions necessitate large-scale human modifications to create the productive agricultural landscape that is visible today.

Okuma (1979) reviewed the history of flood disasters and countermeasures on the Echigo Plain. The transformation of the plain into a major rice-producing area resulted from centuries of hydraulic engineering, including drainage projects, pumping stations, river diversions, and embankment construction, which began during Japan's early modern period during the Edo era (1603-1868). Matsumoto and Koshizawa (2003) analyzed the process of reclaiming canals in downtown Nigata City during the high-growth period. Most citizens supported urban development by reducing waterbodies in the city center.

Nigata City is located at the mouth of the Shinanogawa River. With a population of approximately 800,000, Nigata City is the capital of Nigata Prefecture. Located approximately 250 km northwest of Tokyo, it is approximately 2 h away from the Shinkansen bullet train. Nigata City has developed into a major hub for maritime transportation and has historically served as a

FIGURE 1
Shinanogawa River. Modified from National Land Numerical Information River Dataset and National Land Numerical Information.

vital transportation artery for the country. Additionally, the region's river transportation system plays a significant role in connecting the Shinanogawa and Aganogawa river systems.

## 3.2 Materials and methods

This study adopts a socio-hydrological approach that combines quantitative economic analysis with historical narratives to trace feedback loops between physical interventions and social responses. Government documents, project reports, and literature were reviewed, and a field survey was conducted in July 2025 to examine local conditions of river structure, geography, and socio-economy in the Shinanogawa River Basin. Authors visited Okozu Diversion Channel, reclaimed areas in central Nigata, Sekiya Diversion Channel, main channels, and other key structures. Current river dimensions, embankment conditions, and development patterns were assessed. Government documents, records, data, and related literature were collected.

This study reconstructed detailed economic analyses of major interventions from two perspectives: project-level evaluation using the conventional CBA approach, and system-level evaluation accounting for interdependence and compound effects (Table 1). Conventional project-level CBA suffers from systematic limitations when applied to flood protection in coupled human-water systems. The conventional approach evaluates each project independently in costs and avoided damages, yielding a cost-benefit ratio. Standard evaluation periods of 20-50 years may be too short to capture rare hydrological extremes or delayed consequences of infrastructure decisions. Major floods may have return periods exceeding typical analysis periods, making tail risks invisible to conventional CBA. Evaluating each intervention independently fails to account for system-wide interactions and compound effects. When one project's benefits depend on or are negated by other projects, isolated analysis produces misleading results. Conventional CBA typically cannot account for hidden liabilities—vulnerabilities created by projects that only become apparent decades later or that require future compensatory investments. When protection enables development that reduces flood capacity, this latent vulnerability

TABLE 1 Comparison between conventional analysis and system-level evaluation.

| Dimension | Conventional project-level analysis | System-level evaluation |
|---|---|---|
| Scope | Single intervention | Multiple interdependent projects |
| Time horizon | Project life (20-50 years) | Century-scale (100 + years) |
| Boundary | Project site | Coupled system at the river basin scale |
| Liability treatment | Visible, direct costs | Hidden, emergent liabilities |
| Linkage rules | None | Sequential of flood protection structure, development, and flood capacity |

Source: Author's elaboration.

does not appear in project-level evaluation. Most CBA frameworks assume risk perception remains constant or adjusts rationally to actual risk. They do not model how protection infrastructure alters perceived risk and enables behavioral changes that increase exposure. System-level evaluation links projects sequentially and analyzes together, combining costs and benefits. This reveals hidden liability not apparent in isolated project analysis.

The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) conducted an economic analysis of flood protection projects on the Shinanogawa River. The benefits of these projects include avoided damage costs to structures and buildings, disaster response costs, and disruption costs to economic activities (MLIT, 2022b). The benefits of reclamation were estimated using official government land price data in 2015. Construction costs for all projects were obtained from government documents produced by MLIT and Nigata Prefecture. Gross regional products and other socio-economic statistics were used to provide context for assessing the interventions' relative impacts. The Manning formula, a fundamental hydraulic equation, was used to estimate the river's flood discharge capacities in central Nigata City.

Using the reference year of 2015 enables consistent comparisons to be made across the century of intervention. All costs and benefits were converted to 2015 constant prices using the official deflator series from the MLIT (2022b). The MLIT deflator is the standard methodology used for evaluating Japanese infrastructure projects, providing internal consistency across all analyzed projects. The ministry calculates the deflator using an input cost approach. This involves aggregating the price indices for labor and material costs, which constitute construction project expenses, and weighing them according to their respective proportions. These weights are derived using the input-output table for the construction sector. Nominal values were then discounted to present value using a 4% social discount rate following MLIT guidance, standard for Japanese infrastructure project evaluation. This study's sensitivity analysis focused on discount rate variation (2%, 4% and 6%) as the primary source of uncertainty given the century-scale evaluation period.

# 4 Retrospective analysis of Shinanogawa interventions

This section examines the temporal sequence of the physical interventions involved in the construction of infrastructure and the resulting social responses in Nigata City, which is located downstream of the Shinanogawa River (Figure 2). To promote urban development, protect against flooding, and create a favorable environment, cities have relied on a series of infrastructure projects.

## 4.1 Phase 1: risk reduction enabling urban expansion (eighteenth century-the 1920s)

This phase represents the initial "protection" component of the socio-hydrological feedback cycle. The critical theoretical insight is that major infrastructure fundamentally alters not just physical flood risk but social perception of risk—setting conditions for subsequent development responses. The Okozu Diversion Channel, of 10 km artificial channel, located 60 km upstream from the river mouth, diverts flood flows directly to the Sea of Japan, protecting 210,000 people across 370 km² of land valued at 2.6 trillion yen or 17 billion USD (Hokuriku Regional Development Bureau, 2018).

The project's history reveals the complex socio-political dynamics underlying major hydraulic interventions. Although local farming communities petitioned for the channel in the eighteenth century, construction was delayed by technical limitations, engineering challenges, and competing interests. The construction required extensive excavation, which could not be done solely by human labor. Downstream residents of Nigata City opposed the project because of concerns about water and sediment flow control at Nigata Port, an early manifestation of competing stakeholder interests.

The catastrophic 1896 flood represented a critical system disturbance that overcame institutional inertia and resolved competing interests. The national government commenced construction in 1907, importing heavy machinery and Western engineering technologies (Shinanogawa River Office, 2016). The 17 year construction period, completed in 1924, marked a fundamental reorganization of the human-water relationship in the basin (Okuma, 2007). The Okozu Diversion Channel has protected areas downstream from flood disasters along the main channel of the Shinanogawa River. Saito (1992) estimated that the benefit of reducing flood damage was 4.5 trillion JPY in 1986. The Okozu Channel accomplished its design objectives, protected agricultural land and communities, and generated substantial benefits.

FIGURE 2
Downstream of Shinanogawa River. Modified from National Land Numerical Information River Dataset and National Land Numerical Information.

## 4.2 Phase 2: perceived safety drives irreversible land conversion (the 1930s- the 1940s)

This phase shows the "development" component of the feedback cycle. Protection infrastructure reduced perceived risk, creating political and economic incentives for development. Once river areas were reclaimed and built upon, restoration of flood capacity became practically infeasible. This represents path-dependent lock-in: an initial choice (protection) enabled a subsequent choice (development) that constrained all future options.

Following the completion of the Okozu Channel, the government of Nigata Prefecture initiated a river reclamation program totaling approximately 200 ha (Table 2). This program costs some 223 billion JPY (1.49 billion USD) at 2015 prices, converted using the deflator and social discount rate (Nigata City, 1997). The total value of reclaimed land is estimated at 290 billion JPY (1.9 billion USD) based on land prices announced by the government in 2015. Public facilities, including schools, sports facilities, hospitals, and government offices, were constructed on reclaimed land to enhance the city's infrastructure and service capacity (Nigata City, 2000a). The remaining areas were sold to private-sector developers for residential and commercial construction.

From a project-level investment perspective evaluated at the time, reclamation appeared economically attractive. The estimated value of 63 hectares of land reclaimed in 1933 and 1934 was approximately 50 million JPY, compared to project costs of 3.3 million JPY—a return ratio exceeding 15:1 that provided compelling economic justification. This appeared to maximize social welfare from scarce land resources.

This physical modification reduced the river's flood capacity and increased vulnerability. The river width was narrowed from 800 meters to 273 meters, designed to accommodate 1,530 $m^3/s$ based on the 1925 flood (Nigata Prefecture, 1962; Shinanogawakaryu Work Office, 1985; Nigata City, 1997). According to the Manning's formula of the basic hydraulic equation, this reduction in channel width would reduce the flood discharge capacity by around two-thirds, provided that the channel width is sufficiently large relative to the water depth. The original capacity is estimated to be approximately 4,500 $m^3/s$.

At the time of reclamation, this future vulnerability was not recognized. The design approach reflected the technical knowledge and institutional practices of the time—engineering practice relied on matching capacity to the largest observed flood, with no conception that removing flood capacity might create hidden liability requiring expensive compensatory infrastructure decades later.

TABLE 2 Reclamation in Shinanogawa River in Nigata City.

| Year | Location | Current cost (000) | Cost at 2015 prices billion JPY (million USD) | Area (Ha) |
|---|---|---|---|---|
| 1933 | Bandai bridge to Prefectural Hall | 1773 | 101 (670) | 39 |
| 1934 | West bank | 1423 | 78 (520) | 10 |
| 1934 | Hakusan Sports Park | 110 | 6 (40) | 14 |
| 1942 | Sekiya, Toriyano | 1991 | 38 (250) | 130 |
| **Total** | | | 223 (1,490) | 193 |

Source: Produced from Shinanogawakaryu Work Office (1985).

## 4.3 Phase 3: values shift justifies environmental elimination (the 1950s-the 1960s)

This phase demonstrates how social values shape infrastructure decisions in ways that later generations may view as losses. The dominant development paradigm of the high-growth era treated water bodies as developable space rather than environmental or cultural assets. This value framing justified further irreversible modifications. Values are not static—what one generation views as rational development, another may view as cultural and environmental destruction. This creates a temporal dimension to hidden liabilities: the loss of environmental services and cultural heritage only becomes recognized as a "cost" when social values shift, but by then irreversibility prevents restoration.

During the high-growth period of the 1950s and the 1960s, government organizations prioritized reclamation over the preservation of waterways, reflecting the dominant social values of that era. Beyond the Shinanogawa River, Nigata City reclaimed all 14 canals, totaling 13.2 km, between 1952 and the following decade. This created 10.6 hectares of land for roads and parks (Matsumoto and Koshizawa, 2003). Limited number, eight out of 40, of city council members objected to the reclamation (Nigata City, 2000b). The downtown area of Nigata was originally created with canal networks for navigation within a port town in the seventeenth century. Its nickname, the "willow capital," derived from its scenic, willow-lined canals, gradually disappeared as these waterways were seen as obstacles to modernization rather than assets (Miura, 2008).

## 4.4 Phase 4: disaster interrupts the cycle (the 1960s)

This phase demonstrates how external system shocks can disrupt feedback cycles. The 1964 Niigata earthquake led to reclamation projects being abandoned due to earthquake risk being recognized. From a systems dynamics perspective, this shows that the path of coupled human-water systems depends not only on feedback loops, but also on unpredictable disturbances.

The prefectural government originally planned to reclaim an additional 109 ha of land along the Shinanogawa River by constructing the Sekiya Diversion Channel, which would divert floodwater into the sea. The government planned to sell 73 ha of reclaimed land for 9.89 billion JPY at the 1963 price. Construction costs were estimated at 9 billion JPY for the new Sekiya Diversion Channel and 3 billion JPY for reclamation (Shinanogawakaryu Work Office, 1985). 55% of Nigata City residents were in favor of the reclamation (Nigata City, 2000b). This suggests a change in attitude toward water. Rather than unconditionally supporting development projects involving the filling of water bodies, residents showed attitudes toward protecting the water environment. The reclamation costs amounted to 115 billion JPY, or 0.77 billion USD, in 2015 prices. The estimated land value was 145 billion JPY, or 0.97 billion USD, in 2015 prices.

The 1964 Nigata Earthquake altered the system's trajectory. The earthquake caused ground liquefaction and tsunami inundation in low-lying areas, reducing land value and market demand for reclaimed riverine properties. This disaster forced the abandonment of extensive reclamation plans. Paradoxically, the earthquake prevented a trajectory toward greater vulnerability. Had the full reclamation proceeded, flood capacity would have been further reduced while exposure increased —potentially catastrophic during subsequent flood events.

## 4.5 Phase 5: compensatory infrastructure locks in high-risk state (the 1960-the 1970s)

This phase represents the "liability actualization" stage of the feedback cycle and demonstrates infrastructure path dependency in its starkest form. Once development had reduced flood capacity and created exposure, the system became locked into requiring expensive compensatory infrastructure. This represents a "locked-in" state from which escape is nearly impossible—the developed floodplain cannot be abandoned, so protection must be maintained at increasing cost.

Okuma (1979) argued that the Sekiya Diversion Channel was constructed to compensate for the flood capacity lost through river reclamation. This 1.76 km channel serves two purposes—protecting downtown Nigata from flooding and reducing sedimentation at the Nigata Port. The national government assumed the project after the earthquake and completed its construction in 1972. The channel can divert up to 3,200 $m^3/s$ directly to the Sea of Japan. Combined with the main channel's capacity of 1,000 $m^3/s$, the total flood capacity in downtown Nigata reached 4,200 $m^3/s$ at the once-in-150-year scale flood safety level.

Land reclamation in the river during the 1930s and the 1940s increased flood risks in the Nîgata city center. In addition, the vulnerability of the city was exacerbated further by the channelization and drainage improvements to the tributaries converging with the main channel between the Okozu Diversion Channel and the city center. The Okozu Diversion Channel has protected the areas downstream only along the main channel of the Shinanogawa River. Even after the channel was completed, flood disasters had frequently occurred in areas along tributaries that converged with the main channel. Uchida (1991) analyzed the 1978 flood in a tributary river, identifying limitations in drainage improvements and pumping stations. Sato et al. (2006) evaluated the 2004 flood in another tributary river as having a low probability but high consequences. They argued that the local governments had not prepared for such events. Government organizations had improved the channels and drainage in the tributary areas. Before the improvement works on the tributaries, floodwater inundated the surrounding areas. Afterwards flooding was confined to the river channels, flowing through the main channel into the city center. However, these interventions increased the risk of flooding in the city center by reducing inundation in the upstream tributary areas. This illustrates how optimizing one part of a system can increase risk in other parts.

The Sekiya Diversion Channel has proven to be a cost-effective investment. The channel protected Nigata City from three major flooding events in 1978, 2004, and 2011, with estimated benefits of 11.7 trillion JPY (78 billion USD) at 2015 prices (Table 3; Shinanogawakaryu Work Office, 1985, 2012). This amount was equivalent to 130% of the gross regional product of Nigata Prefecture. Comparing these benefits to the construction costs of 365 billion JPY (2.4 billion USD) at 2015 prices, the benefit-to-cost ratio exceeded 30:1.

From a system-level perspective, the Sekiya Channel represents compensatory infrastructure made necessary by previous development decisions. The reclamation of the 1930s-1940s reduced flood capacity, creating a hidden liability. A counterfactual analysis suggests that if river areas had not been reclaimed, the original flood capacity of approximately 4,500 $m^3/s$ would have remained intact. With selective channel improvements and levee reinforcement, this capacity could have accommodated even the 2011 extreme flood of 3,386 $m^3/s$.

## 4.6 Phase 6: affluence enables value recovery (1987- up to date)

This final phase demonstrates how social values evolve with affluence and how irreversible decisions create permanent losses that become visible only retrospectively. The extremely high benefit-cost ratio for waterfront amenities reveals contemporary demand for the environmental assets eliminated in earlier phases. This represents a form of "regret" built into path-dependent systems—past decisions made under different value frameworks cannot be reversed.

The MLIT started the YASURAGITEI dyke project in 1987 along the Shinanogawa River in central Nigata with gentle slopes, creating waterfront leisure and park spaces. In 2019, 870,000 people visited the green area for events, festivals, walking, and recreation. Hokuriku Regional Development Bureau (2024) estimated the project's benefit at 22 billion JPY (150 million USD) using contingent valuation methods of willingness-to-pay, against construction costs of 0.61 billion JPY (4.1 million USD), a benefit-cost ratio exceeding 36:1.

TABLE 3 Damage costs avoided by Sekiya Diversion Channel.

| Year | Flood volume (m3/s) | Current price billion JPY | 2015 price billion JPY (Billion USD) |
|---|---|---|---|
| 1978 | 2,250 | 700 | 4780 (32) |
| 2004 | 2,485 | 2,000 | 3460 (23) |
| 2011 | 3,386 | 2,800 | 3470 (23) |
| **Total** | | | 11710 (78) |

Source: Shinanogawakaryu Work Office, 1985, 2012.

This high contemporary valuation of waterfront amenities suggests that eliminated water environments during the 1930s-1960s likely had substantial value that was not recognized at the time. The irreversibility of past decisions means these environments cannot be restored when social values shift.

## 5 Economic evaluation contrasting project-level and system-level approaches

This analysis is a contemporary evaluation informed by the most recent socio-hydrological knowledge, analytical capabilities, and value frameworks. Such resources were unavailable to decision-makers in the early Showa period, the 1930s and 40s. Rather than criticizing past decisions in hindsight, this retrospective analysis aims to extract systematic lessons to inform current and future flood protection and development planning in the context of climate change and evolving social values.

The decisions made during the 1930s and the 1940s must be understood in the context of a time when technical capabilities, institutional frameworks, and societal values differed from current standards. It was not until the late 1950s that probabilistic flood risk assessments and advanced hydrological simulation techniques emerged. Hydraulic calculations relied on simplified methods and limited observational data, limiting the ability to analyze system responses to extreme scenarios. The concepts of ecosystem services, environmental impact assessment, and public participation in planning had not yet been established in technical or institutional practices. Postwar reconstruction and rapid economic growth created overwhelming institutional pressure to demonstrate visible progress in development, while environmental awareness remained minimal compared to contemporary standards.

### 5.1 Protection-development-exposure cycle

The Shinanogawa River in central Nigata City is a prime example of the complex co-evolution of human society and water systems. This demonstrates how the feedback loops between physical interventions and social responses can increase and manage vulnerability. Seemingly rational short-term decisions can trigger cascading consequences that reshape physical river systems and social landscapes over timescales ranging from decades to centuries. The irreversible modifications resulting from river reclamation demonstrate how coupled human–water systems can become locked into high-risk trajectories and develop infrastructure via path-dependent processes.

The construction of the Okozu Diversion Channel created a cascade of infrastructure dependencies, highlighting the close link between flood protection and urban development. A series of infrastructure projects supported urbanization and population increases in Nigata City (Figure 3).

However, the physical intervention of the Okozu Channel triggered a critical social response, reducing the perception of flood risk among residents, developers, and government officials. This enabled two-thirds of the original river area in downtown Nigata to be reclaimed for urban purposes. The narrowed river channel reduced flood capacity to a level sufficient only for recorded disasters, failing to manage events beyond historical precedent.

To compensate for the reduced flood capacity, the Sekiya Diversion Channel was constructed in 1972 in response to 150-year flood scenarios. This indicates that investments in river reclamation can create new vulnerabilities that require additional, costly interventions, while the reclamation decisions made in the 1930s and the 1940s seemed rational.

## 5.2 Socio-hydrological model

The cycle in Shinanogawa River is regarded as an example of the levee effect, also known as the 'safe development paradox'. The interventions created a positive feedback loop in which protection enabled urbanization, which in turn increased flood risks and necessitated further infrastructure as pointed out by Di Baldassarre et al. (2015). The system becomes locked in a state of high protection and exposure, making it difficult to escape (Figure 4).

This process should be understood in a dynamic context (Figure 5). Protection enables economic development, which increases exposure and requires larger future investments. The 48 year lag between the Okozu and Sekiya diversions reveals how slowly liability actualization occurs. This explains why initial reclamation decisions seemed rational—consequences only became apparent decades later. It is difficult to reverse the levee effect in favor of sustainable floodplain management as argued by Ding et al. (2023).

## 5.3 Economic analysis from a system perspective

A comprehensive analytical framework yields insights into the economic analysis of Shinanogawa interventions that differ from those produced by conventional CBA of individual projects. The practical consequences of the methodological choices made are stark: project-level evaluations indicated that all of the interventions were economically justified, whereas system-level evaluations revealed that they had a collective negative value. This section systematically contrasts two evaluation frameworks to demonstrate how methodological choices can lead to different conclusions about the same interventions.

### 5.3.1 Project-level evaluation results

Table 4a summarizes the key economic parameters of the projects at 2015 prices. Under conventional project-level evaluation, each intervention appears economically successful when analyzed independently: This evaluation framework provided decision-makers with apparently sound economic justification for proceeding.

- **Reclamation projects (1930s-1940s)**: Generated land values of 290 billion JPY (1.9 billion USD) against costs of 223 billion JPY (1.5 billion USD) at 2015 prices, producing a positive net benefit of 67 billion JPY.
- **Abandoned 1963 reclamation**: Would have produced estimated benefits of 145 billion JPY (0.97 billion USD) against costs of 115 billion JPY (0.77 billion USD) yielding a net benefit of 30 billion JPY.
- **Sekiya Diversion Channel**: Prevented an estimated 11,710 billion JPY (78 billion USD) in flood damage across three major events in 1978, 2004, and 2011, at a construction cost of 365 billion JPY (2.4 billion USD). This yields a benefit-cost ratio exceeding 30: 1.

### 5.3.2 System-level evaluation results

A comprehensive system analysis that accounts for interdependence among interventions reveals a different picture of economic performance (Table 4b).

- **Reclamation + compensatory infrastructure**: When the historical reclamation projects of the 1930s and the 1940s were analyzed together with the Sekiya Diversion Channel, which necessitated compensatory infrastructure, the combined interventions generated 290 billion JPY in land value against total costs of 588 (223+365) billion JPY, producing a net system loss of 298 (290-588) billion JPY. This perspective reveals that profitable reclamation projects deliver a negative net economic value when their full system implications are properly considered. Reclamation created a hidden liability in the form of reduced flood capacity that had not been recognized for decades, ultimately requiring compensatory infrastructure that cost more than its economic value.
- **Full system risk analysis**: The most comprehensive full-system risk analysis incorporates not only the realized interventions but also the catastrophic scenarios that the Sekiya channel avoided. Without the channel, the three major floods would have caused damage estimated at 11,710 billion JPY. Thus, the total cost is estimated at 11,933 (11,710+ 223) billion JPY. When this potential damage is incorporated alongside the land value created, the net system outcome under the catastrophic scenario reaches a negative 11,647

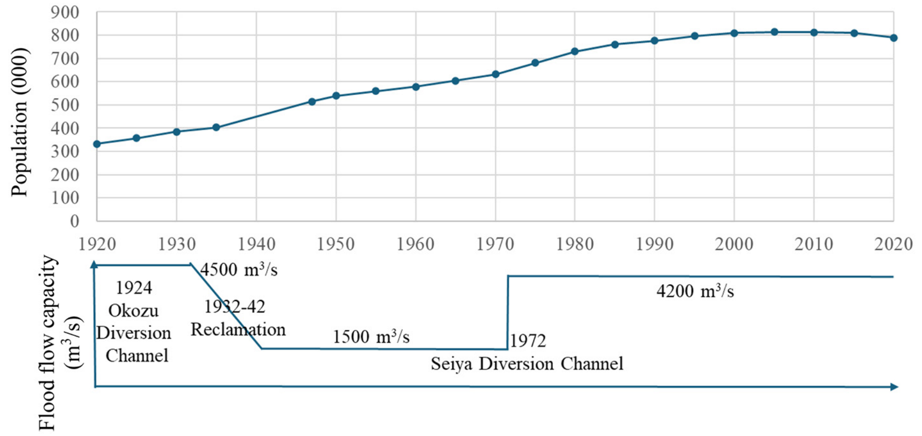

FIGURE 3
Trends of population and flood capacity in Central Nigata City. Source: Author.

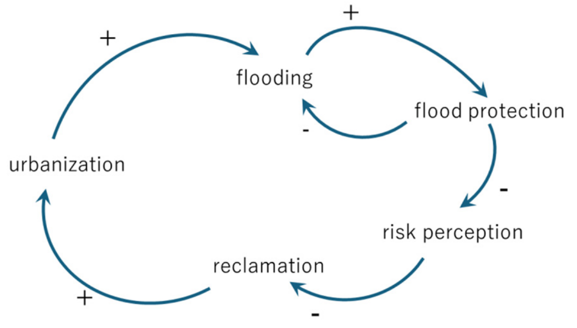

FIGURE 4
Socio-hydrological model in Nigata. Source: Author.

(290-11,937) billion JPY. This analysis revealed the enormous hidden liability embedded in development decisions, which reduces system resilience while increasing exposure.

### 5.3.3 Sensitivity analysis

A sensitivity analysis was conducted to examine uncertainty, using discount rates of 2 and 6 per cent, as well as the base case of 4 per cent (Table 5). This sensitivity analysis demonstrates that while discount rate assumptions affect magnitudes, the fundamental conclusion—that project-level "success" masks system-level negative outcomes—holds across the plausible parameter range.

As the evaluation period spans almost 100 years, even slight variations in the discount rate impact on the net benefit values. The reclamation project from the 1930s and 1940s is evaluated positively with discount ratios of 2 or 4 percent, but negatively with 6 percent. Higher returns are required to recoup investment over such a long period. Similarly, the net benefit of the entire system increased from 11.9 trillion JPY to 18.4 trillion JPY. The abandoned reclamation project also became negative with a 6% discount ratio.

### 5.3.4 Counterfactual analysis

A rigorous counterfactual analysis can strengthen causal inference regarding the effects on the entire system. Such an analysis demonstrates that preserving natural capacity offers resilience benefits which are not visible at project level, but which can be quantified through system-level analysis.

Had river areas not been reclaimed, the original flood capacity of around 4,500 $m^3$/s would have remained intact. With selective channel improvements and levee reinforcement, this capacity would have been sufficient to accommodate the 2011 extreme flood (3,386 $m^3$/s), making the Sekiya Diversion Channel unnecessary.

# 6 Discussion and broader implications

## 6.1 Short-term optimization and long-term vulnerability

Divergent economic assessments illuminate the critical temporal dynamics in coupled human-water systems. From the pure investment perspective evaluated at the time of construction, the initial land reclamation appeared attractive. The price of 63 ha of land reclaimed in 1933 and 1934 was estimated at approximately 50 million JPY, compared to the project costs of 3.3 million JPY. This return on investment provides economic justification for reclamation from a short-term perspective. However, a long-term evaluation of 2015 prices reveal a narrower margin, with land values of 290 billion JPY, exceeding the reclamation costs of 223 billion JPY.

Similarly, the abandoned 1963 reclamation project appeared attractive from the short-term financial perspective available at the time of planning. The project was designed to generate 9.89 billion JPY in land sales, against 3 billion JPY in construction costs, resulting in a favorable return ratio. Long-term estimates at 2015 prices show benefits of 145 billion JPY against costs of 115 billion JPY, a narrower margin when properly accounting for long-term costs and benefits.

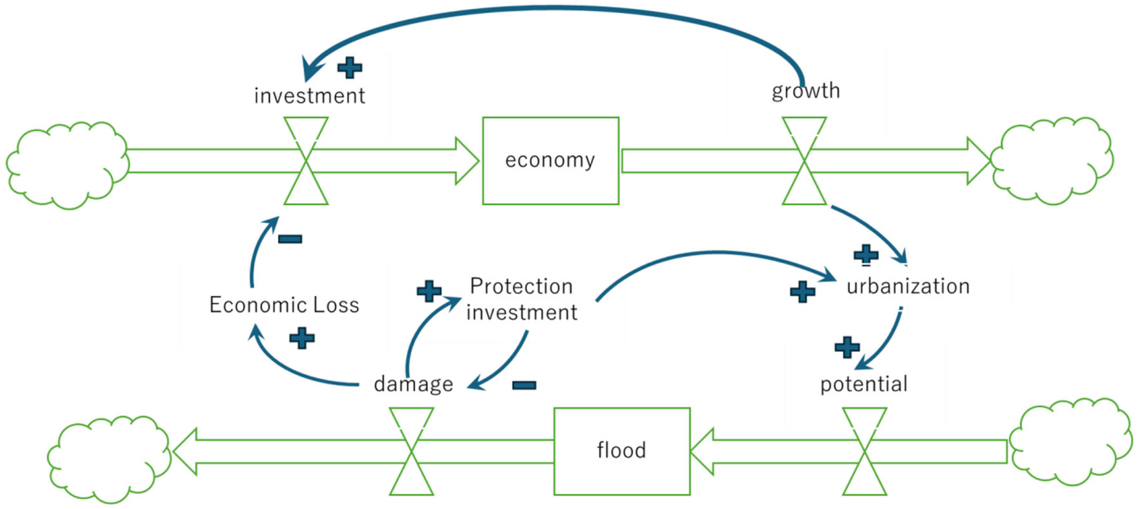

FIGURE 5
Stock-flow model in Nigata. Source: Author.

TABLE 4 System level evaluation.

| (a) Figures related to measures billion JPY (billion USD) | | (b) Reclamation cost and benefit | |
|---|---|---|---|
| Reclamation cost 1933-42 | 223 (1.5) | Benefit | 290 |
| Value of land reclaimed 1933-42 | 290 (1.9) | | |
| Sekiya Diversion cost | 365 (2.4) | Cost Reclamation + Sekiya Div. | 588 |
| Damage cost avoided by Sekiya Diversion | 11710 (78) | Benefit-Cost | −298 |
| Reclamation cost (abandoned plan) | 115 (0.77) | | |
| Value of land reclaimed (abandoned plan) | 145 (0.97) | | |
| YASURAGITEI cost | 0.61 (0.0041) | Cost Reclamation + Damage cost | 11,933 |
| YASURAKITEI benefit | 22 (0.15) | Benefit-Cost | −11,643 |

Source: Author.

TABLE 5 Sensitivity analysis: net benefit (benefit-cost, billion JPY).

| Project | Discount ratio | | |
|---|---|---|---|
| | Base 4% | 2% | 6% |
| Reclamation project 1933-42 | 67 | 243 | −738 |
| Sekiya diversion | 11,345 | 8,186 | 905 |
| Reclamation abandoned plan | 30 | 103 | −165 |
| SYSTEM | −11643 | −8,095 | −18,426 |

Source: Author's elaboration.

The finding that seemingly profitable projects can yield negative system-level outcomes underscores the risks of shortsighted management. When focusing on short-term returns, decision makers may undervalue long-term system resilience and fail to anticipate dependencies that only become apparent decades later and can have a cascading effect.

The fundamental driver is temporal mismatch between human decision-making timeframes (years to decades) and hydrological event frequencies (decades to centuries). The 48-year lag between Okozu Channel completion (1924) and Sekiya Channel completion (1972) illustrates this. The vulnerability created by reclamation did not actualize until major floods tested the reduced capacity (1978, 2004, and 2011). Infrastructure agencies are rewarded for building, not for preserving capacity.

## 6.2 Changing value of water

As socio-economic changes have altered society's valuation of water, Niigata City has lost its cultural and environmental heritage. This demonstrates the irreversibility of coupled environmental-hydrological modifications and the path-dependent nature of vulnerability lock-in. The substantial parts of main channel of Shinanogawa River were reclaimed in the 1930s and 40s, losing both environmental and hydrological functions. Furthermore, during the period of rapid economic growth in the 1950s and 1960s, the city filled all downtown waterways to construct urban infrastructure such as roads and buildings. These waterways were once essential to urban life, providing transportation, drainage, cooling, and landscape enhancement. They also support aquatic and riparian ecosystems and play a role in shaping the city's cultural identity. Nigata City was once known as the 'City of Willows,' thanks to the beautiful willow trees that lined waterways.

Launched in 1987, the Yasuragitei dike project demonstrated citizens' demand for waterfront environments, with a cost-benefit ratio of over 36:1. With 870,000 visitors annually, this green space demonstrates the value of citizens place on access to water and waterfront amenities in urban environments.

As societies become more affluent and basic developmental needs are met, preferences shift toward environmental and aesthetic amenities and quality of life. The willingness to pay for waterfront amenities implies that the loss of the water system represents a significant reduction in quality of life and environmental services from a contemporary perspective.

### 6.3 Generalizability: comparison with other rivers

While the Shinanogawa case provides detailed documentation of century-scale feedback, the question of generalizability remains. A comparative framework identifying levee-effect indicators is summarized through comparing other cases (Table 6).

All systems show similar dynamics—initial protection enabling development, capacity reduction, and compensatory structure. The protection-development-exposure cycle appears generalizable. The Shinanogawa case provides a prototype for detecting similar patterns in other basins.

## 7 Lessons learned

### 7.1 Lessons and policy implications

Standard economic evaluation frameworks systematically fail to capture hidden liabilities and cumulative effects emerging over several decades. Each intervention evaluated independently showed positive returns, obscuring the negative system-level outcome. The mismatch between the timeframes of human decision-making, which span years to decades, and the frequencies of hydrological events, which span decades to centuries, is the fundamental issue. The 48 year lag between protection projects on the Shinanogawa River is an example of this. Once flood capacity has been eliminated through development, restoration is generally infeasible due to multiple forms of irreversibility. This path dependency locks systems into states that require ever-increasing protection infrastructure. The shift in perception of water bodies from obstacles to development in the 1930s-1960s to quality-of-life amenities from the 1980s to the present day demonstrates that future generations may value environmental assets differently.

### 7.2 Implications for CBA methodology

The primary policy implication is that conventional project-level CBA is inadequate for evaluating interventions in coupled human–water systems. Best practice would involve a system-level analysis linking related interventions and an extended time horizon of over 100 years for irreversible decisions. It would also require explicit accounting for hidden liabilities and the valuation of preserved flood capacity and resilience. Decisions that irreversibly modify natural systems should be subject to particular scrutiny. A higher burden of proof should be applied to projects that irreversibly reduce flood capacity. Climate change amplifies the importance of these lessons. Future precipitation patterns will differ from historical records, making the preservation of flood capacity and resilience even more critical.

### 7.3 Limitations and future research directions

Given the significant impact of discounting on net present value calculations over a 100 year evaluation period, the study conducted a sensitivity analysis with variations in the discount rate serving as the primary source of uncertainty. However, there are other sources of uncertainty. Specifying the damage function specifications, translating flood depth into monetary losses, involves modeling assumptions that introduce uncertainty into the estimated avoided damages. Using the MLIT deflator to convert construction costs over periods exceeding 80 years—particularly during wartime economic turmoil in the 1940s—may introduce errors into historical cost figures. Nevertheless, the qualitative conclusion that project-level evaluations mask negative system-level outcomes remains robust, as it is derived from the structural relationship between successive interventions rather than precise parameter estimates. Future research should build upon this methodological approach.

The economic value of the reclaimed land was estimated using the official government land prices published in 2015 and applied to the specific parcels of land created through the reclamation process. This method determines the value of land based on its current use, reflecting the cumulative effects of nine decades of urban development, infrastructure investment, and intensified land use. Consequently, it captures the realized contemporary value rather than the anticipated value at the time of reclamation. This is consistent with the retrospective analytical framework of the study, which evaluates system-level outcomes from a contemporary perspective. However, this methodology may overestimate the value attributable to the reclamation itself, since some of the current land value reflects subsequent public and private investments in urban infrastructure that are not related to the original reclamation decision. Conversely, this approach does not capture the opportunity cost of alternative uses of the river space, including environmental services and flood conveyance capacity, which the system-level analysis addresses separately through compensatory infrastructure costs.

This study identifies several avenues for future research. Future work should test levee-effect indicators across other basins

TABLE 6 Comparison with New Orleans and Rhine basin.

| System-level indicator | Shinanogawa | New Orleans | Rhine basin |
|---|---|---|---|
| Initial major protection | 1924 Okozu channel | 1930s—50s levee projects | Nineteenth century channelization and embankment led by Tulla-Honsell |
| Development surge post-protection | 1930s—1960s reclamation and development | 1950s—1990s urban sprawl | Nineteenth century development in flood plains |
| Hidden liability actualized | 2004, 2011 floods | 2005 Hurricane Katrina | 1995 Rhine flood, Waternood |
| Compensatory infrastructure response | Sekiya channel | Post-Katrina levee reinforcement | New embankments and retention areas |

Source: Author's elaboration based on Burby (2006) and Ikeuchi et al. (2000).

to identify whether the protection-development-exposure cycle represents a general pattern and which basin-specific factors (geology, institutional capacity, development context) modulate its severity. Quantitative modeling of feedback loops and time delays could formalize the relationship between protection infrastructure, risk perception, development expansion, and exposure accumulation, improving prediction of when hidden liabilities become actualized. Ecosystem service assessment methods and historical willingness-to-pay approaches could more comprehensively quantify cultural heritage losses and environmental service flows, strengthening arguments for environmental preservation in planning decisions. The interaction between infrastructure lock-in and changing precipitation patterns deserves dedicated analysis, particularly for developing regions where climate adaptation and flood management strategies are currently being designed. Research into organizational structures and incentive mechanisms that enable century-scale planning, cross-project accounting, and reversal of path-dependent infrastructure decisions could inform governance innovations necessary for sustainable flood management.

# 8 Conclusion

The Shinanogawa River case reveals a fundamental paradox in flood management. Rational short-term decisions, individually justified at the time they are made, collectively produce long-term system trajectories that increase vulnerability and require ever-increasing compensatory investment. This paradox is not unique to Nigata, nor is it a failure of decision makers in the early Showa period. Rather, it represents a systemic feature of how flood protection investments and social responses co-evolve interconnectively. Irreversible projects, such as land reclamation, should be examined from a longer-term perspective rather than the current 50 year flood planning horizon. System-level analysis that links sequential interventions can reveal hidden liabilities not apparent in project-by-project evaluation. Conventional cost-benefit frameworks inadequately capture tail risks and compound system effects.

This study demonstrates the "levee effect" or "safe development paradox" not as a one-time mistake, but as a structural feature. The system is locked in high protection and exposure, making reversal or restructuring difficult and costly. Temporal mismatch is critical—human decision-making operates on timescales of years to decades, whereas hydrological extremes operate on timescales of decades to centuries. Along the Shinanogawa River, the initial flood protection infrastructure reduced perceived risk, triggering political and economic incentives for development. This development irreversibly modified the physical system and reduced the flood capacity. Compensatory infrastructure addressing vulnerability created by earlier decisions may exceed the benefits of original projects, suggesting that preventing vulnerability creation is more cost-effective than remediation.

When irreversibly modifying natural systems, societies should preserve what they do not fully understand as having value. The environmental and cultural values of waterbodies, which are difficult to quantify, represent significant public goods that warrant consideration for preservation in urban development planning. This represents a reversal of the social value of urban water bodies. Where water was once viewed primarily as a developable space, contemporary society has increasingly valued it for environmental, recreational, and cultural services. Environmental and cultural values warrant preservation consideration in planning, even when difficult to quantify, given that future generations' preferences may differ from current valuations.

Flood management strategies must adapt to climate change and evolve in line with societal values. Predictions of future precipitation patterns suggest that they may differ from historical records, making scenario-based approaches increasingly important. To avoid repeating the costly cycle of short-term development gains that lead to long-term vulnerabilities, future flood protection investments should be informed by integrating advanced technical capabilities and an evolved environmental consciousness. Modern hydrological simulation techniques, probabilistic flood risk assessments, and climate change projection capabilities provide the necessary tools for long-term planning. Attitudes toward river environments have evolved as recognition of their ecological, cultural, and recreational value has grown.

# Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.reinfolib.mlit.go.jp/, Real Estate Information Library and https://www.pref.niigata.lg.jp/site/tokei/, Nigata prefecture statistics.

## Author contributions

MI: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing. TF: Conceptualization, Methodology, Resources, Validation, Writing – review & editing. AK: Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing, Validation.

## Funding

The author(s) declared that financial support was received for this work and/or its publication. Financial support for this research has been provided by the Foundation of River & basin Integrated Communications (FRICS) Research Grant.

## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. During the preparation of this work, the author(s) used Grammarly and Claude to check the grammar and language of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2026.1748569/full#supplementary-material

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