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Estimating the Economic Viability of Long-Term Investment in Flood Protection: Case Study of the Natorigawa River

Mikio Ishiwatari,* Masashi Sakamoto,† and Daisuke Sasaki‡

Abstract

Investments in disaster risk reduction are essential for mitigating disaster damage, an aim stressed by the Sendai Framework for Disaster Reduction. While a cost-benefit analysis is usually conducted for flood protection projects to confirm the viability of any new project, long-term economic analysis at the river basin or the regional scale has rarely been conducted. Policymakers need evidence that investments in flood protection contribute to regional growth. This study proposes a methodology for economic analysis of flood protection investments at the river basin scale and applies it to the Natorigawa River basin as a case study. The study estimates benefits, both past and future, by reducing damage caused by observed and simulated floods. It finds that the methodology is applicable and investments over the last seven decades in the river basin have been efficient, with an estimated benefit-cost ratio of 6.1. The methodology needs to be further simplified for application to developing countries, given the limited data and capacity in these countries. Moreover, methods for estimating the effects of climate change and the cost of replacing facilities need to be developed.

Keywords: Investment for DRR, Cost-benefit analysis, Flood simulation, Evidence-based policymaking

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1. Introduction

It is widely recognized that investments in disaster risk reduction (DRR) are essential for mitigating disaster damage. The Sendai Framework for DRR 2015–2030 (UNISDR 2015), adopted at the Third United Nations World Conference on Disaster Risk Reduction in Sendai in 2015, states that "Budgets for disaster risk reduction are not an expense or cost but an investment in the future." The framework stresses the importance of ex-ante investment in DRR to reduce losses and prevent stagnation of economic development. The framework sets out four priority actions: 1) understanding disaster risk, 2) strengthening disaster risk governance to manage disaster risk, 3) investing in DRR for resilience, and 4) improving effective disaster response preparedness and employing a "Build Back Better" approach in the recovery and reconstruction process.

While the importance of ex-ante investment is widely acknowledged as necessary for reducing disaster risks, as emphasized in the Sendai Framework, financing this goal has remained a challenge for many countries (Ishiwatari and Surjan 2019; Mizutori 2020). To increase DRR investment, policymakers need evidence that such investments can contribute to regional and national growth, yet such evidence is rarely available (Ishiwatari 2019).

Economic analysis at the project scale is conducted widely, utilizing a variety of methods. For example, the Japanese government conducts evaluation, re-evaluation, and post-evaluation for flood protection projects at the planning stage, during, and after each project, respectively. A cost-benefit analysis evaluates the project with a focus on the efficiency of the investment. If the evaluation shows low efficiency, the project may be discontinued.

These conventional analyses are conducted to evaluate the viability of specific projects, not to assess to what extent a series of flood protection measures can contribute to regional growth. Reducing flood damage promotes development activities and enhances growth at the regional level. Confirming the efficiency of long-term investments is crucial for making policies.

This study aims at establishing a methodology for estimating the efficiency of long-term investment in flood protection at the river basin scale. It reviews recent literature related to the economic analysis of flood protection to develop a method for economic analysis. It then proposes a new method and applies it to analyze economic benefits and costs for past investments in flood protection in the Natorigawa River basin, which flows through Sendai City, Japan, as a case study.

2. Flood protection investment and economic analysis

This section examines the issues of economic analysis of flood protection measures by reviewing recent literature. It further examines economic analyses of actual measures used for flood protection in Japan and selected major countries. These countries have suffered from flood disasters and developed policies and countermeasures for flood protection. Like Japan, cost-benefit analysis in the Netherlands, Germany, and the United States has focused largely on project costs and their benefits and seldom evaluates long-term investments and their effects at the river basin or regional scale.

2.1 Issues of economic analysis on flood protection investment

Recent literature on the economic analysis of flood protection measures primarily analyzes projects but seldom provides substantive analysis of past investments at the regional or river basin scale. The economic benefits of flood protection can be divided into the stock effects of mitigating direct and indirect damage, as well as the consequent effects of the monetary flows produced from project implementation (MLIT 2020, Figure 1). Direct benefits include the protection of physical assets such as houses, offices, factories, equipment, machinery, and infrastructure from damage caused by flooding.

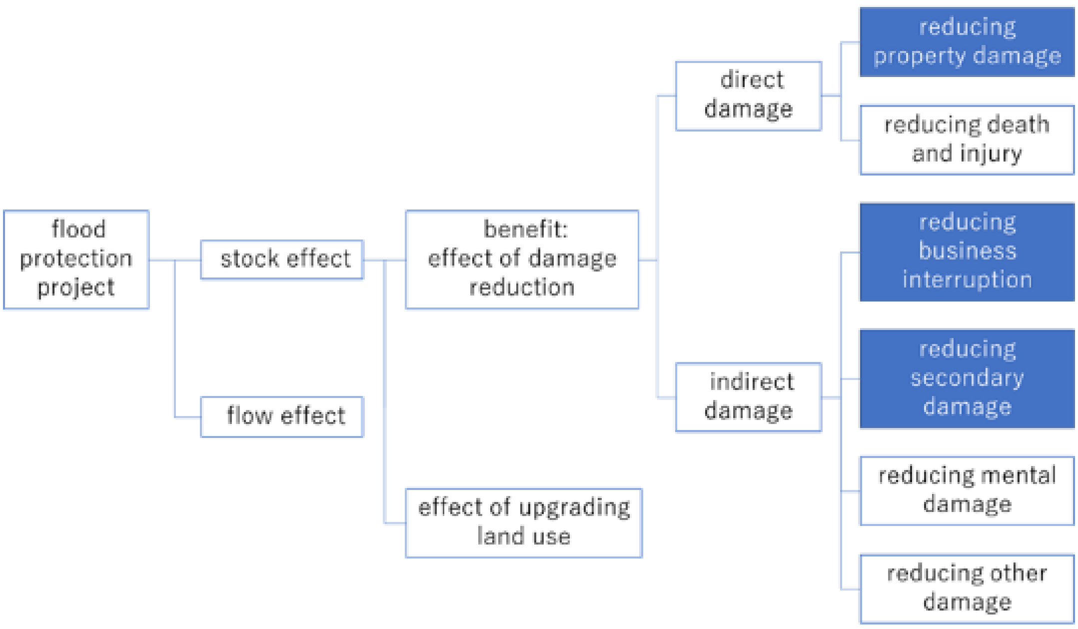

Figure 1: Economic Effects of Flood Protection Projects

Source: MLIT, 2020

Note: Dark boxes show factors included in Japanese analysis.

Indirect benefits are equally important and cover a broader range of impacts. These include preventing the stoppage of public services and private operations due to flood damage, each of which can have cascading effects on the economy and society. Flood protection investments can also reduce the need for response activities by households, the private sector, and governments. Such investments can help to mitigate the mental distress that is often experienced by individuals and communities affected by floods. They can help prevent other damage, such as the contamination of water sources and the spread of water-borne diseases. However, economic analysis is unable to capture some cascading effects, such as the welfare effects on health, education, and the environment, as well as mental distress (Sakamoto, Sasaki, and Ishiwatari 2022). Human life is rarely evaluated in monetary terms due to ethical concerns (Messner and Meyer 2005).

Merz et al. (2010) pointed out that there is limited data on flood damage, which is necessary for economic analysis. Although three steps are required to assess damage—classifying the elements at risk, quantifying exposed asset values, and assessing direct economic damage—methods and data for all three steps have not been sufficiently developed. Even with this limited data, some studies have attempted to conduct economic analyses in river basins. Marchand et al. (2020) evaluate an embankment project using socioeconomic exposure maps and damage and casualty functions in the Brahmani–Baitarani River, India. Shrestha and Kawasaki (2020) evaluate the economic benefits of reducing flood damage through dam operations in the Bago River Basin of Myanmar.

JICA (1998) evaluated the benefits of water resource management projects over the last 40 years in the Brantas River basin in Indonesia. The agency estimates the construction costs of flood protection works at JPY 85 billion, or USD 610 million, and the benefits of saving flood damage at JPY 13.5 billion, or USD 96 million, annually. The methodology of the estimation is not described.

Recent studies cover economic analysis of climate change adaptation at the global scale. Ward et al. (2017) conducted cost-benefit analyses of structural flood protection measures considering climate change effects and found that dike construction is an efficient investment. Dottori et al. (2018) project that direct economic damage from river flooding is likely to double globally with a 2°C rise in temperatures.

2.2 Cost-benefit analysis in Japan

Japan has struggled with flooding for most of its 2000-year history (Ranghieri and Ishiwatari 2014). Following the modernization of political and socioeconomic systems starting at the end of the 19th century, the country developed legislation, budgetary systems, and institutions to manage flood disasters (Ishiwatari and Sasaki 2022). The River Law was enacted in 1896 to promote the development of national flood protection projects.

The government formulated the first long-term plan for flood protection after the nationwide flood disaster of 1910. Since then, the flood protection plan has been revised in accordance with socioeconomic changes (Matsuura, 1986). With the enactment of the revised River Law in 1964, government organizations formulated a basic plan for implementing river works in each river basin to establish a system for flood protection and water utilization to meet increasing demands during the period of high growth. With the 1997 amendment of the River Law, the basic plan was changed to a master plan for the river basin, the Basic Policy for River Development, and a River Development Plan, which provides a 20–30-year action plan. These policies and plans aim at developing a comprehensive system for flood protection, water utilization, and environmental preservation. Environmental preservation was added as an objective to restore the river environment damaged during the period of high growth.

The Japanese government has begun a review of its flood protection plans to reflect the effects of climate change. There is concern that climate change will lead to greater damage due to more frequent and more intense heavy rainfall. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) projects that flood risks will double because of the effects of climate change under the Representative Concentration Pathway 2.6 scenario, in which temperature increases by 2°C. This is consistent with the target of the Paris Agreement, an international framework established at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change held in Paris, France, in 2015 (MLIT 2021).

In Japan, project benefits cover the stock benefits of direct benefits resulting from preventing the loss of property values caused by floods to residences, offices and factories, crops, and infrastructure. Indirect benefits include preventing the disruption of business activities and emergency responses to protect homes, offices, and local governments. These damage costs are estimated based on past damage surveys in the country. The factors identified by dark boxes in Figure 1 can be considered benefits. The benefits calculated in the project evaluation do not cover other forms of damage, such as loss of life or deterioration in health.

Figure 2 shows the Japanese approach to the cost-benefit analysis of flood protection. The costs and benefits are compared after converting them to present-day values using social discount rates and deflation (MLIT 2018). Benefits are estimated by considering the probability of flood occurrence.

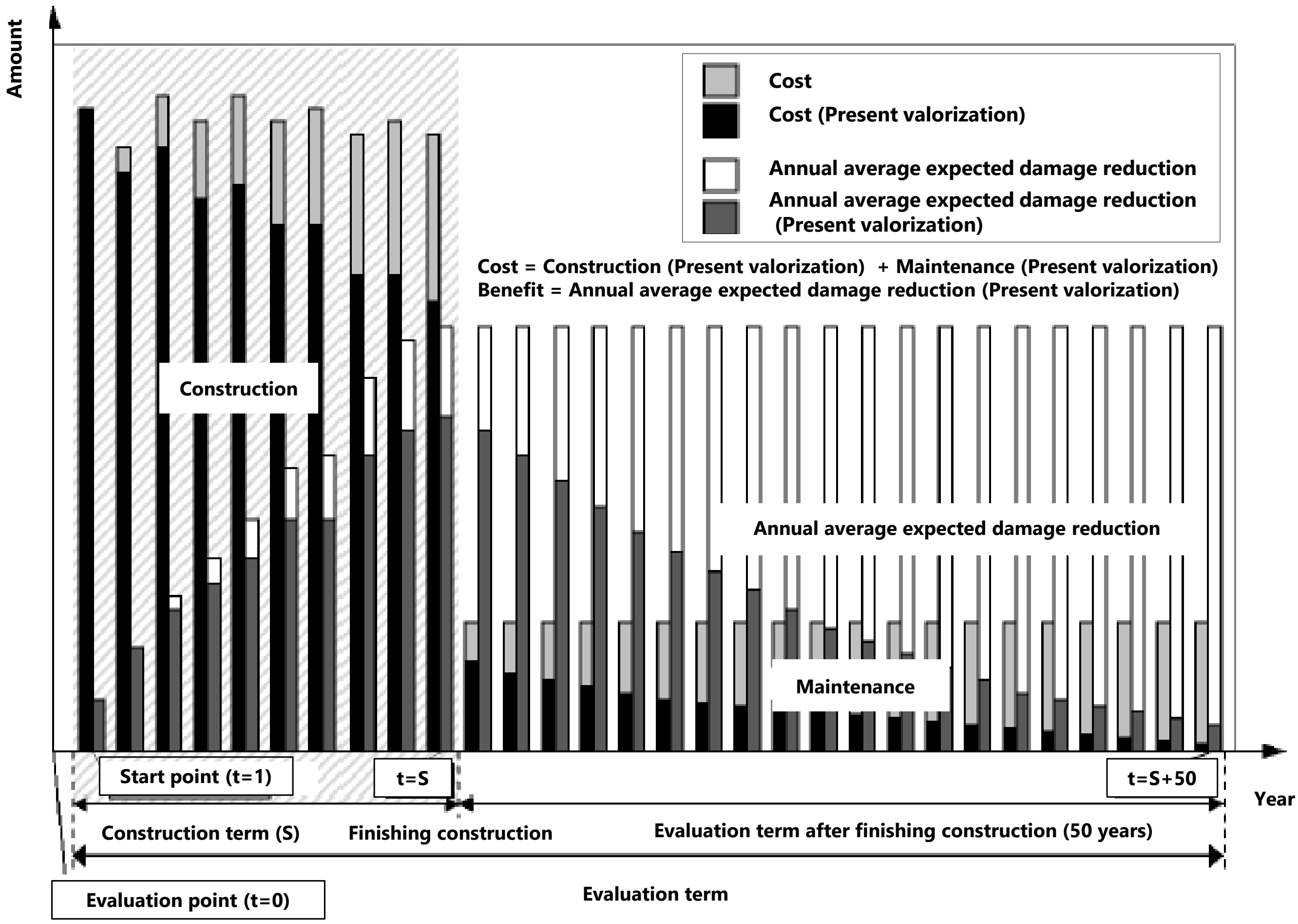

Figure 2: Concept of economic analysis on flood protection in Japan

Source: MLIT (2020)

2.3 Flood protection investment and economic analysis in selected countries

The Netherlands is a low-lying country with about one-fourth of its land area below sea level. The Netherlands has experienced repeated floods and has built dikes around the country to mitigate damage. The North Sea flood of 1953 caused extensive damage, killing 1,800 people. In response to this damage, a large-scale project plan, the Delta Plan, was developed, with numerous facilities constructed over the past four decades (Technical Review Committee on Climate Change Projection in the Hokkaido Region (Water Sector) 2018). The Delta Committee is implementing measures to improve flood protection standards considering climate change impacts, with the target year of 2050. The "KNMI06 Climate Scenario" of the Netherlands Meteorological Office estimates that the future planned flow of the Rhine River will increase to 18,000 m^3/s, and this value has been adopted as the standard for adaptation planning. (Yanagisawa and Wakigawa 2011). Projects are promoted on the basis of risk ratios. The tolerable risk of death from flooding was set at 1/100,000 based on political judgment and social cost-benefit analysis. With this as a target, the government is implementing dyke reinforcement projects and other measures (Tomura et al. 2018).

Germany has developed a unified flood risk management plan using the framework of the Federal and State Working Groups on Water Affairs. The 2002 Elbe River floods led the Federal Ministry for the Environment to develop the "Basic Principles in Flood Protection, or Five Key Programmes." These principles provide guidance on flood risk reduction, mainly through floodplain identification and management. Climate change is projected to increase winter precipitation by 40% and decrease summer precipitation by 40%. The country is considering increasing the frequency and scale of floods (Yanagisawa and Wakigawa 2011). Each project is evaluated according to cost-benefit analysis, using average annual damage and benefits. Rather than simply evaluating the benefit-cost of a single flood, the analysis is conducted for various flood events with different return periods (Meyer and Messner 2005).

In the United States, the Army Corps of Engineers implemented flood protection works in major rivers, such as the Mississippi River. Since the 1970s, land use and building regulations have been implemented through the flood insurance system. Hurricane Katrina in 2005 caused extensive damage because of overflows and dike breaches. Payments to meet insurance claims put pressure on flood insurance operations, reaffirming the need for investments in dike safety management and flood protection projects to improve the efficiency of floodplain policies (Yanagisawa and Wakigawa 2011). Flood damage reduction projects implemented by the Federal Emergency Management Agency rely on a simple metric: project benefits exceed the project costs (McGee 2021).

3. Methodology of economic analysis

3.1 Developing a new methodology: Basic concepts

While the current conventional analysis aims to evaluate economic viability in the future for new projects, this study proposes a methodology of economic analysis based on past investments in flood protection. The Ministry of Construction, currently MLIT, Japan developed its methodologies for economic analysis of flood protection projects over half a century ago—in 1957—and issued a manual for economic analysis in 1961 (Takebayashi and Yasuda 1995). The purpose of their methodology is to examine the appropriateness of flood protection projects to be implemented by comparing the benefits of the projects with the costs required to construct and operate and maintain the facilities.

3.1.1. Benefits assessment

This study assesses both past and future benefits of investment, covering the effects of mitigating flood damage resulting from any structures developed (Figure 3). Past benefits are estimated by calculating the estimated damage without the structure minus the actual damage.

Future benefits are estimated by multiplying expected annual damage (EAD) reduction with the number of years of an evaluation period. Damage reduction for each flood volume scale of selected probability is the gap between damage with and without the structure. First, the EAD reduction for each flood volume size is calculated by multiplying the damage reduction amount determined for each volume size by the probability of occurrence of that flood. These are then accumulated to calculate the expected EAD reduction.

Damage costs are calculated as the replacement value of reconstructing assets damaged. For each river basin, asset data on housing, infrastructure, offices, factories, and agricultural lands are collected. Damage costs for each asset group are then estimated by multiplying the value of assets by the damage ratio based on the depth of inundation (MLIT 2020). For example, the damage ratio for housing is less than 7% when inundation depth is less than 50cm, increasing to 20% and over 80% at 50 cm and 300 cm inundation depth, respectively. Inundation depths are determined through flood simulations, conducted according to the MLIT manual (MLIT 2015). This assessment generates estimates of the expected depth of inundation based on the size and frequency of potential floods. The Ministry has determined damage ratios by asset group based on damage surveys conducted in the past.

To consider the effects of urbanization, the benefits calculated are reduced by the ratio of the residential area at the time of the disaster to the present day. Ignoring the impact of urbanization would result in an overestimation of damage.

This study uses a simple linear model of the rates of flood volumes to reduce the number of flood simulations. As the first step in estimating past benefits, the amount of economic damage for the largest flood in the record was calculated under the scenario of no structure constructed.

To calculate economic damage without any structures for each major flood event in the past, the damage cost for the largest flood is then multiplied by the ratio of each flood volume to that of the largest flood. These are explained by equation (1):

$$Dmi = Dmax\frac{Vmi}{Vmax} \quad (1)$$

where D_{mi} is economic damage without the structure caused by a targeted past major flood i-th; D_{max} is the economic damage without the structure caused by the largest flood in the record; V_{mi} is the volume of the past flood i-th; and Vmax is the volume of the largest flood in the record.

For future benefits, this study uses a simple linear model of the rates of economic damage caused by floods with the scales of selected probabilities to the one with the safety level planned under the assumption of structure completed by investment to date. MLIT estimated economic damage with the structure caused by selected floods to reevaluate the program in Natorigawa River (Tohoku Regional Development Bureau, MLIT 2018). The damage caused by the flood of the planned safety level without the structure was calculated as the base case. Flood damage without the structure for each flood scale according to a probability selected is calculated by equation (2).

$$\mathrm{DWO}j = \mathrm{DWO}saf\,\frac{\mathrm{DW}j}{\mathrm{DW}saf} \quad (2)$$

where DWO_j is damage without the structure caused by a flood with the scale of once in *j* year; DWO*saf* is the damage caused by flood with the scale of safety level without structure as the base case; DW_j is the damage with the structure by the flood of the scale of once in *j* year; and DW*saf* is the damage with the structure caused by the flood using the safety level scale, which is determened by the ministry for promoting flood protection measures. In the case of Natorigawa River, the safety level is set at once-in-150 years. Other flood scales cover once in 10 years, 20 years, 30 years, 40 years, 50 years, 60 years, 70 years, 80 years, and 100 years.

3.1.2 Cost estimation

For past costs, river improvement and dam construction costs during the construction period are collected from MLIT and Miyagi Prefecture government. For future analysis, the evaluation period is set at 50 years considering the depreciation period of facilities. Construction costs are assumed to be zero, and only the maintenance and operation are included. The costs of replacing facilities are not included.

These costs and benefits are converted into present values and real prices using social discount rates and deflators (MLIT 2020; Table 1). No deflators are applied to the past benefits, which are estimated based on the current asset values.

Table 1: Concept of Present Valuation and Real Pricing

	Cost		**Benefit**	
	Past	**Future**	**Past**	**Future**
Social discount rate	Apply	Apply	Apply	Apply
Deflator	Apply	Not apply	Not apply	Not apply

Source: Modified from MLIT, 2020

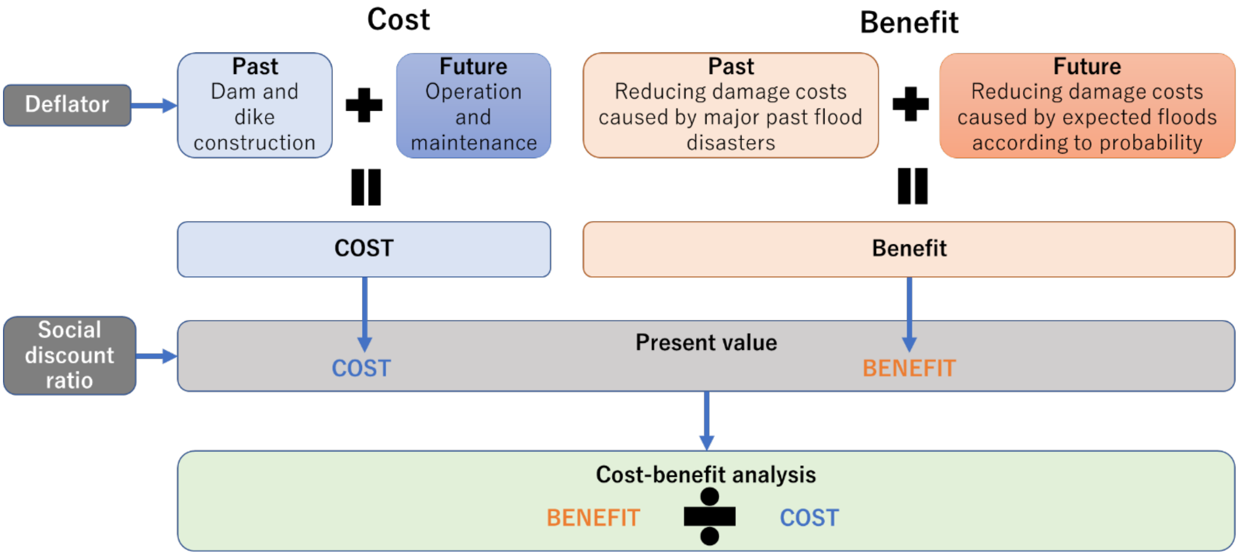

Figure 3: Concept of economic analysis on past investments in flood protection at the river basin scale

3.2 Case study of the Natorigawa River Basin

The methodology proposed is applied to the Natorigawa River Basin to examine its applicability to a real-world case. The basin is located in the center of Miyagi Prefecture and flows through Sendai city, the main city of the Tohoku region.

3.2.1 Charactaristics of Natorigawa River Basin

The Natorigawa River is a first-class river managed by MLIT. It begins at the Miyagi and Yamagata prefectural border, merges with the Hirose River and several other small and medium-sized rivers, and flows through Sendai City and into the Pacific Ocean at Yuriage, Natori City (Figure 4). It has a main channel length of 55.0 km with a watershed area of 939 km^2. The river basin consists of Sendai, Natori, and Iwanuma, Kawasaki, and Murata cities.

The land use in the watershed is approximately 76% mountain forests, 12% agricultural land such as rice paddy fields, and 12% urban areas. The population of the urban areas in the river basin has increased year by year since the early 1930s, reaching approximately 1.1 million in

2000 (Figure 5). In 1975, the population of the basin accounted for about 41% of the total population of Miyagi Prefecture, and by 2010, it had reached about 50% (Tohoku Regional Development Bureau, MLIT 2012), indicating that the population is increasingly concentrated in the river basin.

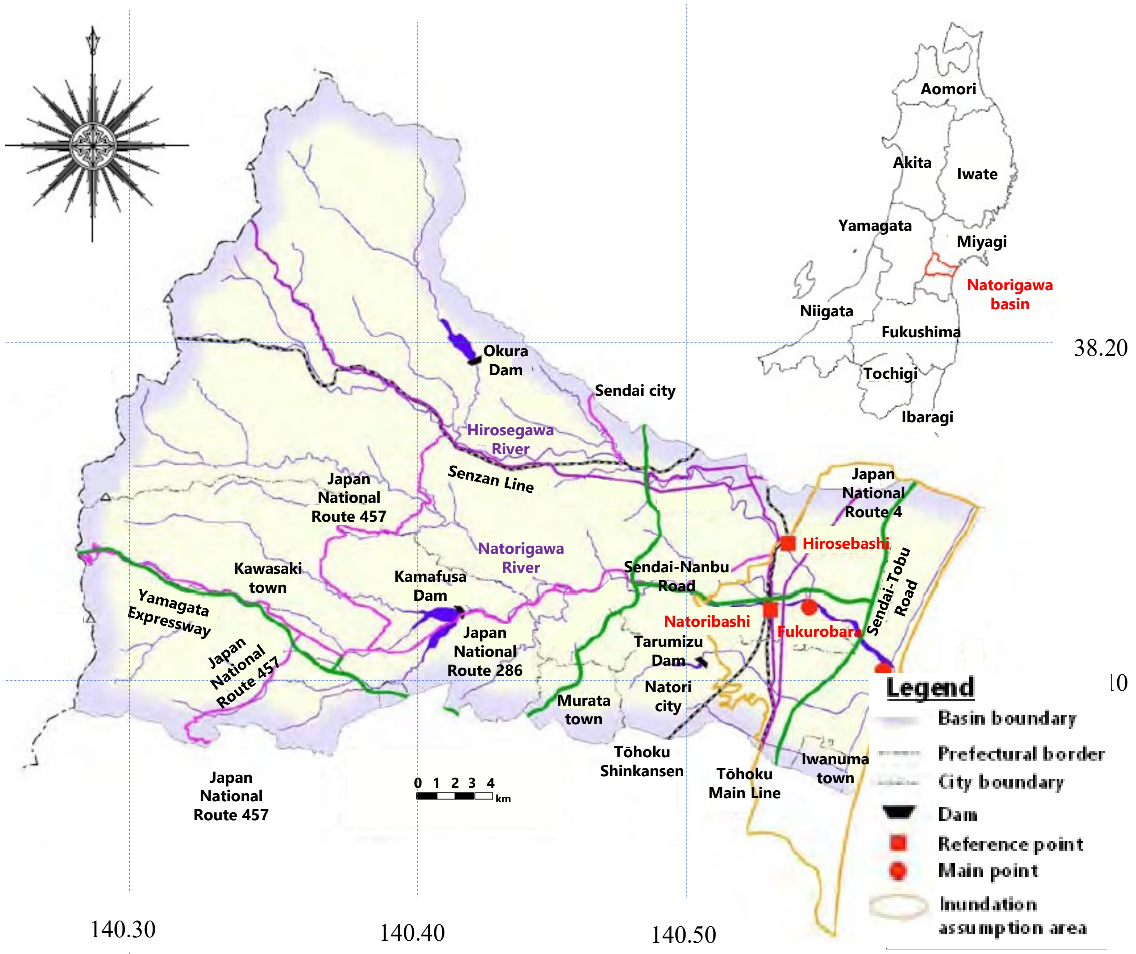

Figure 4: Natorigawa River Basin map

Source: Tohoku Regional Development Bureau, MLIT, 2012

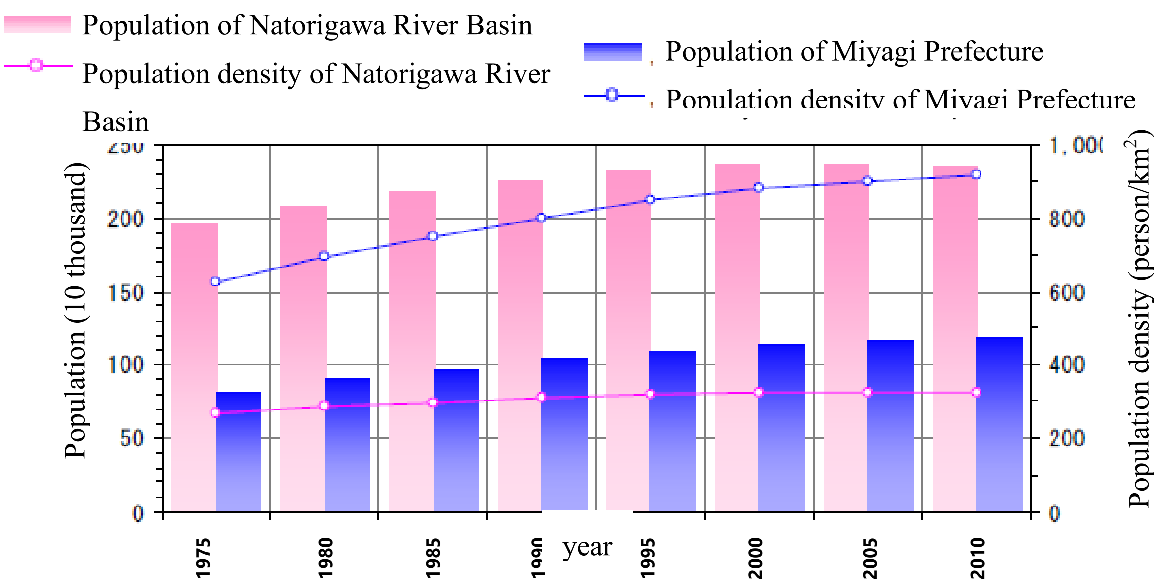

Figure 5: Population and Population Density of Municipalities in the Natorigawa River Basin
Source: Tohoku Regional Development Bureau, MLIT, 2012

3.2.2 Investment in flood protection works

The calculation flow of economic analysis in the river basin is shown in Figure 6. The evaluation period is set for 118 years by combining the past investment period from 1951 to 2018 and the future evaluation period from 2018 until 2068.

The river basin experienced a series of floods in 1947, 1948, and 1950. To respond to these flood disasters, MLIT formulated the first flood protection plan in 1954. MLIT commenced dike construction projects in 1951 and had completed almost all major works by 1985 (Tohoku Regional Development Bureau, MLIT 2012). The government subsequently revised the plan, modifying the designed high-water level to cope with the widespread land subsidence caused by the Great East Japan Earthquake in 2011.

There are two major dams: the Kamafusa Dam, managed by MLIT, and the Okura Dam, managed by Miyagi Prefecture. The Kamabusa Dam is a 45.5-meter-high gravity concrete dam constructed on the Goishigawa River in the Natorigawa River system in 1971. The Okura Dam, an 82-meter-high arch-type concrete dam, was constructed on the Okuragawa River in 1961. These are multi-purpose dams designed for flood protection and water supply to Sendai City and other central Miyagi Prefecture areas.

River improvement costs from 1951 were provided by MLIT. The cost of dam construction was divided by the construction period for each year's cost. The total project cost of the Kamabusa Dam was JPY 8.72 billion (USD 62.3 million), and the construction period was five years from 1966 to 1970. The total project cost of the Okura Dam was JPY 2.76 billion (USD 19.7 million), and the construction period was four years, from 1958 to 1961. The operation and maintenance costs were provided by MLIT. The past and future costs were converted to the present value using deflators and a social discount rate of 4%, which MLIT uses for the economic analysis of infrastructure projects (MLIT 2020).

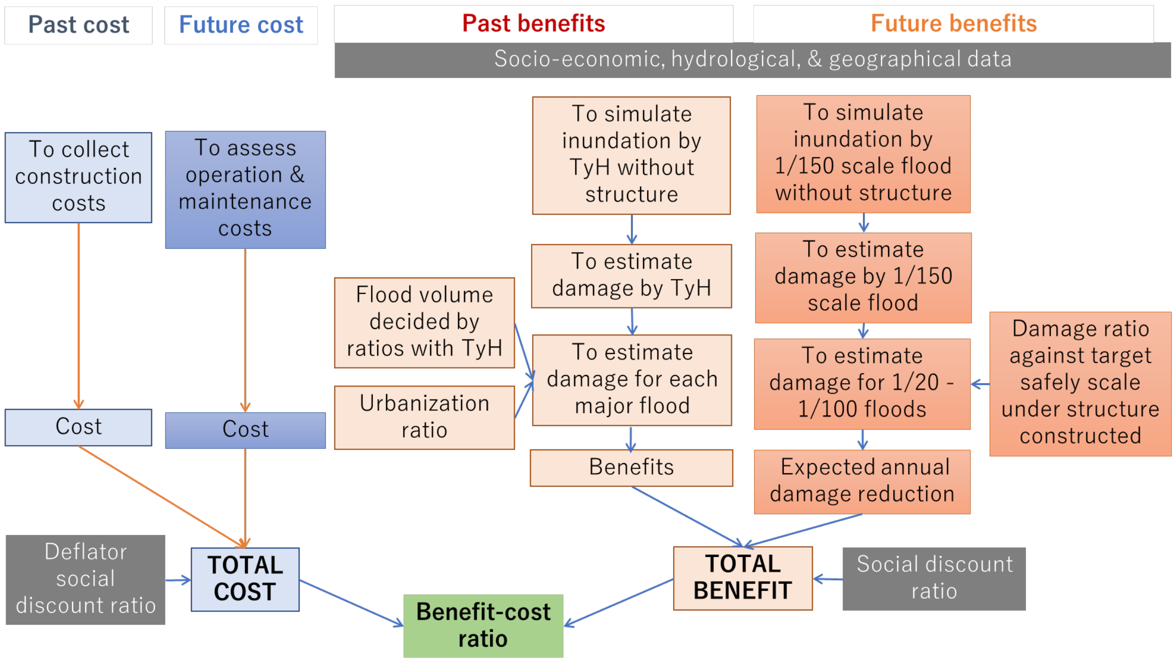

Figure 6 : Calculation flow

TyH: Typhoon No 19, Hagibis

3.2.3 Conditions for benefit estimation

The past benefits were calculated by accumulating damages that would have been caused by major floods without any construction of structures. This assumption can be justified since major river works were completed in 1985, and the major floods covered in this study occurred after 1986. Structures have provided protection for risk areas from these major floods, and damage costs were relatively small compared with damage without structures. For example, the flood disaster in 1994 caused JPY 122 million (USD 0.87 million) compared to the JPY 240 billion (USD 1.7 billion) of damage estimated to have occurred without the structures. The Tohoku Regional Development Bureau (2012) identified six major floods since 1951, in addition to one caused by Typhoon No. 19, Hagibis, in 2019.

Typhoon Hagibis brought record-breaking rainfall to many observation points in the Kanto, Koshin, and Tohoku regions (Ishiwatari 2022). It collapsed river dykes at 142 locations across Japan. The total damage amounted to approximately 1.86 trillion yen (USD 13.3 billion), which is the highest figure ever recorded for flood damage. It resulted in 87 people reported dead or missing, 21,000 houses destroyed, and 60,000 houses flooded (MLIT 2022).

Damages were calculated using equation (1). Typhoon Hagibis caused the largest flood volume on record in the Natorigawa River basin. Damage amounts were calculated and tabulated for each mesh according to inundation depths resulting from flood simulations. A table organizing the assets within the inundation blocks as basic quantities is presented in Appendix A.

Future benefits were calculated for an evaluation period of 50 years. Since MLIT is promoting flood protection works with the safety level of a once-in-150-year flood, the base case was set at the flood level of once-in-150 years. The amount of damage for each of the ten flow-scale patterns based on 10 probability years from once-in-10 year to once-in-150 year was calculated as in equation (2) (Table 4). This was multiplied by the interval probability, difference between adjacent average annual exceedance probabilities, to obtain the annual average EAD reduction.

3.2.4 Inundation assessment by flood simulation

The flood simulation model, developed by MLIT for its detailed project analysis, was used under the assumption of no investments. The simulation results for Typhoon Hagibis were used for the base case to estimate past benefits and 1/150 of the probability scale flood of the safety level for future benefits.

The areas analyzed are located along river sections managed by MLIT and divided into three blocks, L-1, L-2, and R-1 (Figure 7). Land use conditions were determined based on 1/10 subdivision land-use mesh data, which is the tertiary mesh of the 2014 National Land Survey Data. Ground elevations, dikes, and box culvert conditions were prepared from the endpoint elevations of the urban planning map. Survey data in March 2016 were used for examining land development after the Great East Japan Earthquake in 2011 to simulate future floods. A list of geographic information data is provided in Appendix B.

In establishing the river channel model without flood protection investment, the surveyed point of ground elevation in the river areas and the mean high waterbed elevation were compared, and the higher point was considered the highest point of the river channel. For the upstream end boundary condition, the upstream end flow was determined based on the results of the runoff calculation using the storage function method.

The recorded flood hydrograph of Typhoon Hagibis was used to make the hydrographs of flood volumes and waves under the condition that there was no upstream dam. For the downstream single boundary condition, the water level of the August 1986 flood—the highest water level on record—was used as the downstream end water level. Flood discharge from the river channel was calculated using the storage function method, and inundation of flood plains was calculated using a 2-dimensional unsteady flow.

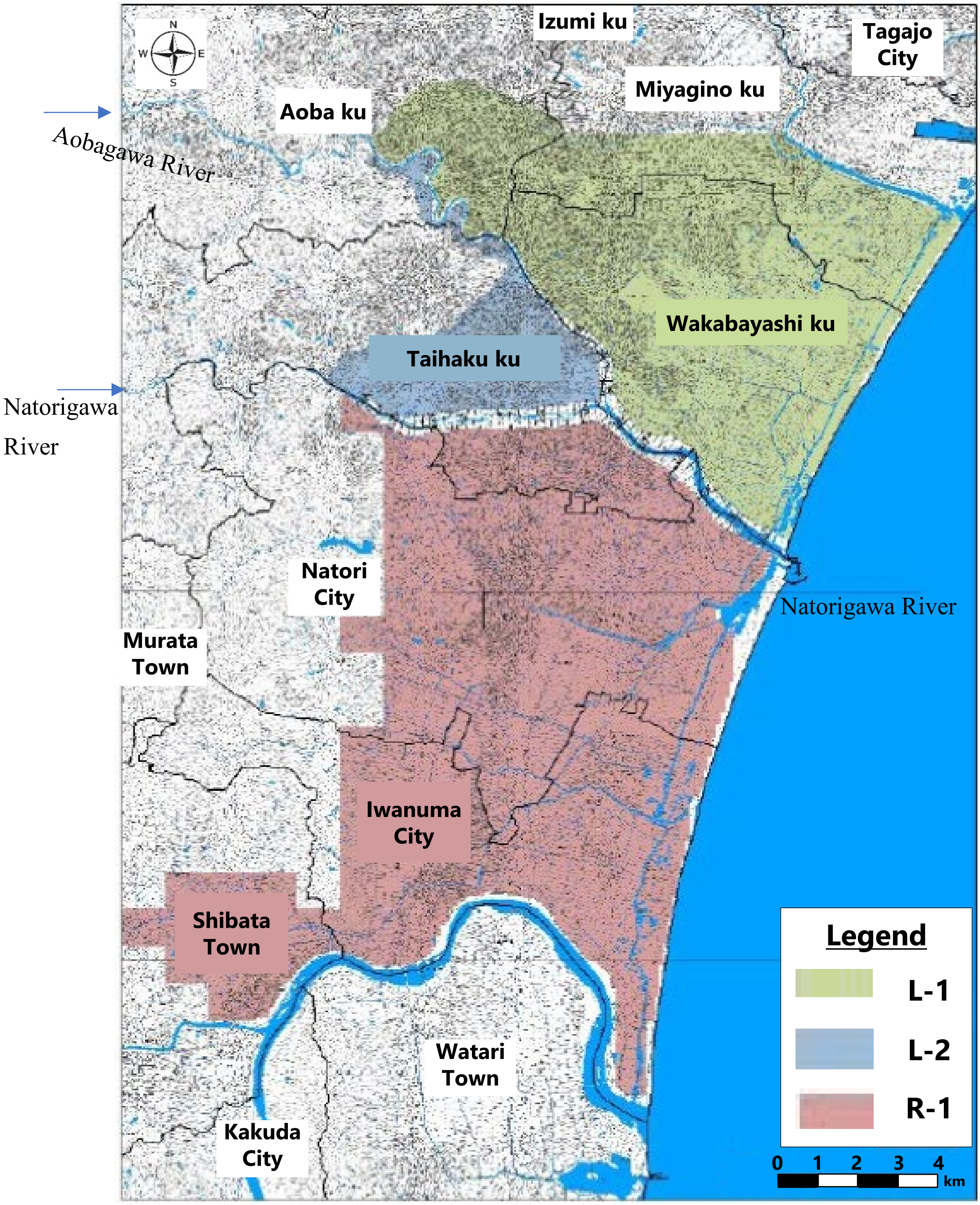

Figure 7: Inundation block division

Source: Modified from Tohoku Regional Development Bureau, MLIT, 2012

4. Results

4.1 Cost estimation

For past costs, river improvement costs and dam construction costs were totaled and converted to present value prices (Figure 8). The total cost was 624.6 billion JPY (USD 4.5 billion) based on current value. The future costs were the total operation and maintenance costs provided by MLIT over the past 50 years and were converted to present values. The total future cost was JPY 1.5 billion (USD 10.7 million).

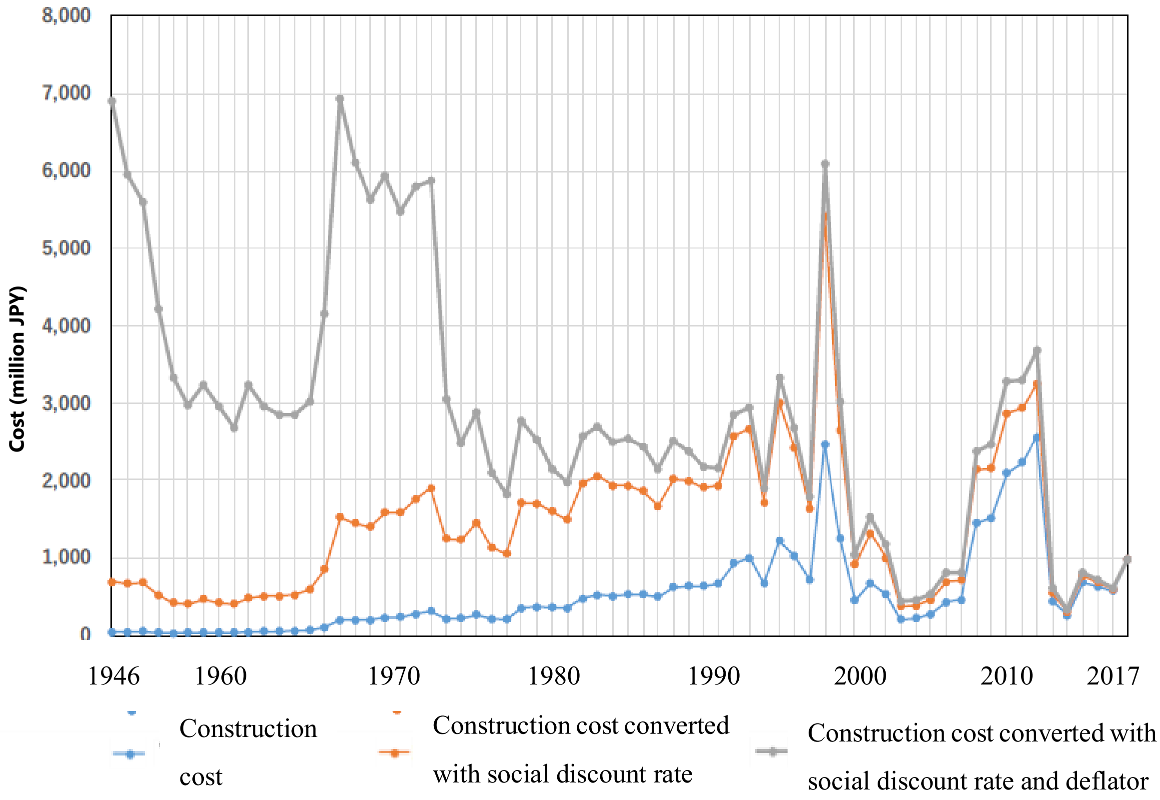

Figure 8: Trend of construction costs

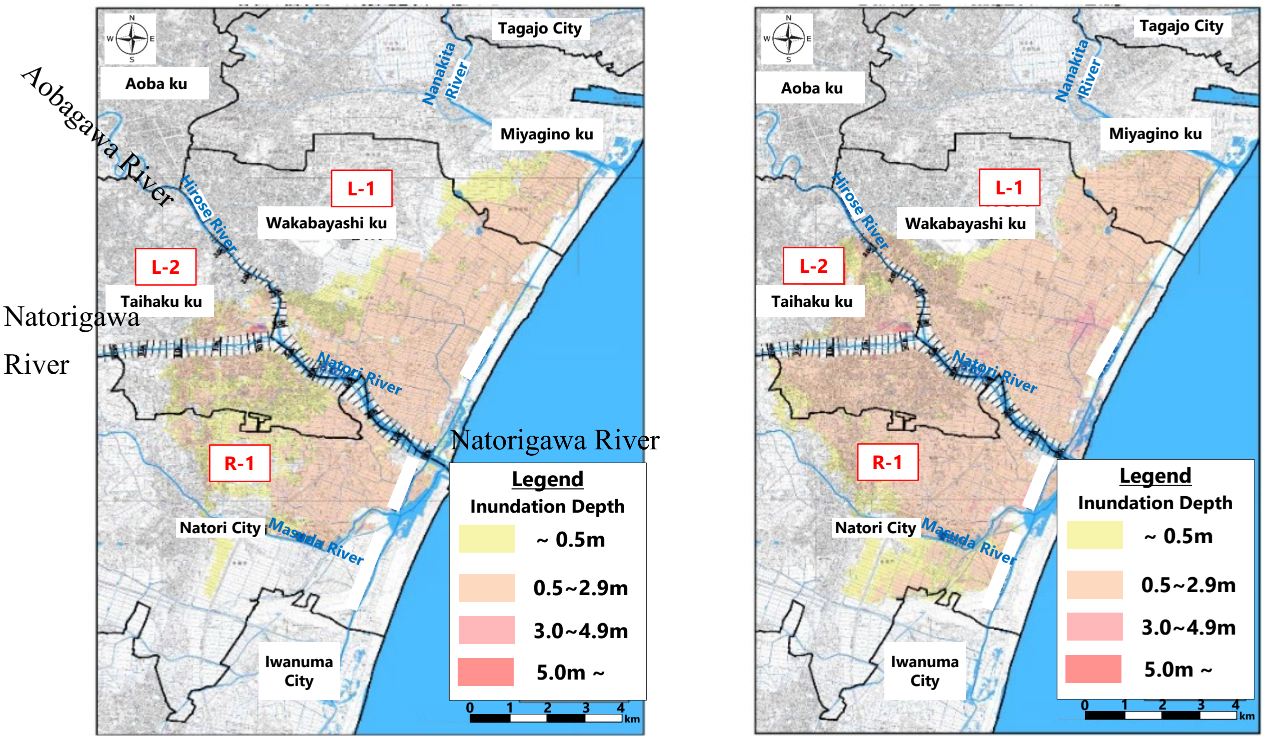

Figure 9: Inundation map (left: Typhoon No. 19 in 2019, right: 1/150 scale flood with annual probability of exceedance)

4.2 Benefits

4.2.1 Results of flood simulation

To estimate the benefits, the maximum inundation areas and depths were estimated by conducting flood simulations, as shown in Figure 9. Compared to Typhoon Hagibis, the 1/150-year flood was expected to inundate more areas.

4.2.2 Past benefit calculation

Damage caused by Typhoon Hagibis as the base case was assessed under conditions of no investment (Table 2). The amount of damage was JPY 350 billion (USD 2.5 billion). Most of the damage was to houses, offices, and public facilities. General assets accounted for 36% and crops 0%. Public facilities accounted for 60%, and other emergency measures accounted for 4% (Figure 10).

The amount of damage per flooded block was at its highest in Block R1 at JPY 240 billion (USD1.7 billion). This was more than twice the total of the JPY 41 billion (USD 290 million) damage in Block L1 and the JPY 68 billion (USD 486 million) damage in Block L2 (Figure 10). Block R1 is located on the right bank of Natorigawa River, where new housing developments are underway in the urban area of Natori City and Sendai City (Figures 7 and 9). The L1 block on the left bank is severely damaged by the 2011 Great East Japan Earthquake and Tsunami and was designated as a disaster risk zone, which restricts development activities. On the other hand, agricultural lands such as rice paddies have been preserved, and the amount of agricultural damage was the highest in this area (Figure 11). The L2 block on the left bank side, which is close to downtown Sendai and has a high concentration of offices and commercial facilities, had the highest amount of damage to business assets.

The total benefits of structure mitigating the effects of past major floods was estimated to be JPY 3.7 trillion (USD 26.4 billion). The benefits of the six major floods were calculated according to equitation (1) (Table 3).

4.2.3 Future benefit estimation

The damage caused by a flood occurring once in a 150-year scale was estimated at JPY 1.3 trillion (USD 9.3 billion) without any structures. This damage decreased to JPY 260 billion (USD 1.9 billion) with structures. Thus, benefits were estimated at JPY 1.05 trillion (USD 7.5 billion) as the base case once the 1/150 scale flood happens (Table 4).

The average EAD reduction amount was JPY 4,998 million (USD 35.7 million). The amount of damage for each of the ten flow scale patterns based on probability years was calculated using equation (2). The patterns cover flood scales of once in 10 years, 20 years, 30 years, 40 years, 50 years, 60 years, 70 years, 80 years, 100 years and 150 years. This was multiplied by the interval probability to obtain the annual EAD reduction. This annual EAD of JPY 4,998 million (USD 35.7 million) was accumulated for the total future benefits for 50 years by conversion to a present value using a social discount rate of 4%. The total future benefits were estimated at JPY 112 billion (USD 800 million).

4.3 Validation

To validate the results, the results were compared with figures calculated in a MLIT project evaluation (Table 5). The ministry evaluated the future programs in the Natorigawa River Basin that will be built on top of facilities completed to date, and in the course of its evaluation work, estimated the current damage caused by a once-in-150-year flood to be JPY 261 billion (USD 1.86 billion) (Tohoku Regional Development Bureau, MLIT 2018). In addition, MLIT estimated the benefits of the future program to be implemented to be JPY 31 billion (USD 220 million). In contrast, this study estimated the damage from a once-in-150-year flood to be JPY 1,047 billion (USD 7.48 billion) and the future benefits to be JPY 112 billion (USD 0.8 billion) without the facilities. The difference is the effect of facilities constructed to date. The ratios of the figures of these two estimates are 4.0 and 3.6.

Table 2: Damage due to Typhoon No. 19, Hagibis (2019) under condition of no investment

(Million JPY)

Block	Assets							Agricultural products			Public Facilities	Business stoppage	Household emergency measures			Office emergency measures	TOTAL
	House	House-hold goods	Business		Agriculture and fishery		Sub-total	Rice	Crops	Sub-total							
			Depreciable assets	Inventory assets	Depreciable assets	Inventory assets							Cleaning	Alternative activity	Sub-total		
L1	8,815	3,771	1,256	432	38	16	14,328	393	99	491	24,271	549	280	493	773	261	**40,673**
L2	7,727	5,414	10,819	728	6	2	24,697	7	12	19	41,836	769	271	430	701	210	**68,233**
R1	41,879	30,953	9,951	2,482	50	20	85,335	193	60	247	144,558	3,314	1,723	2,858	4,581	1,328	**239,363**
Total	58,420	40,138	22,026	3,642	94	38	124,359	592	171	757	210,665	4,633	2,274	3,782	6,056	1,799	**348,269**

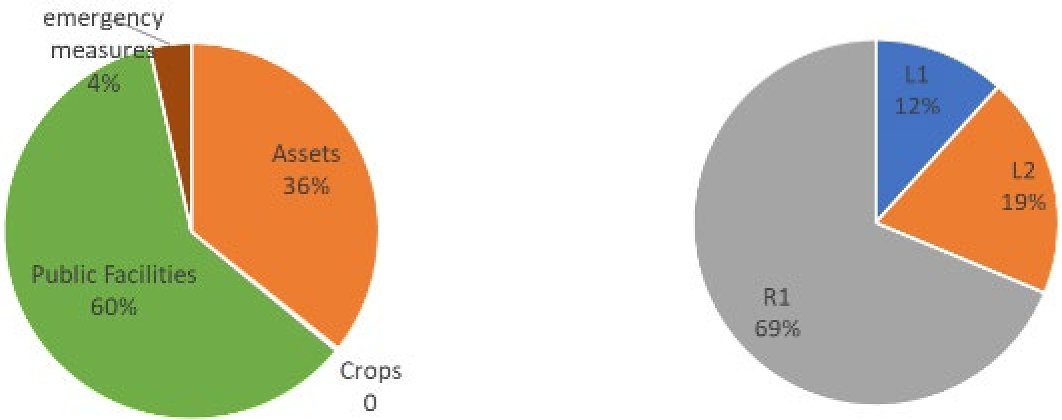

Figure 10: Breakdown of estimated damage by Typhoon No. 19, Hagibis (2019) under condition of no investment, Left: Per damage characteristic and Right: Per flooded block

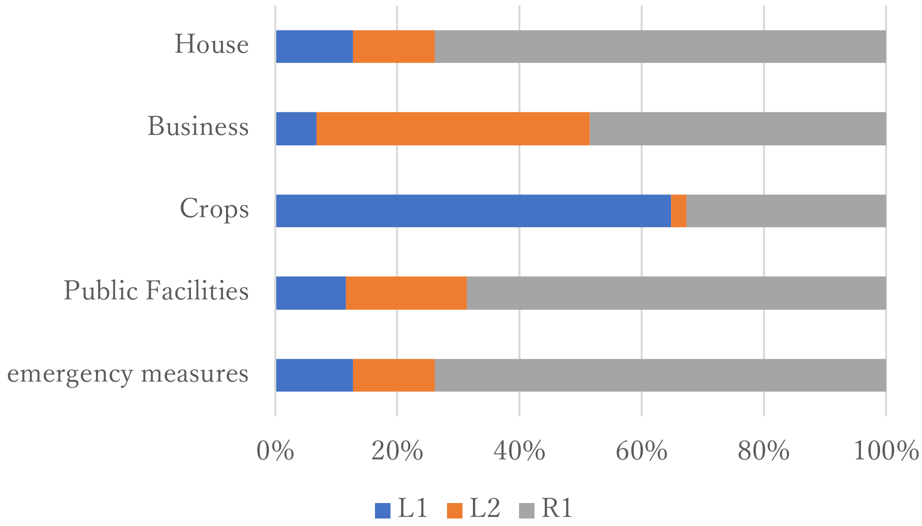

Figure 11: Share of damage by block

Table 3: Benefits resulting from structures constructed in past major floods

	Flow volume (m^3/s)	Ratio of flow volume to Typhoon Hagibis	Benefits (without reduction of urbanization) (without present valorization) (Million JPY)	Residential land (ha)	Ratio of residential land to 2019	Reduction by social discount ratio 4%	Benefit (With Urbanization compensation) (With present valorization) (Million JPY)
August 1986	2,690	0.82	283,892	12,003	0.76	3.51	754,952
August 1989	3,280	0.99	346,158	13,253	0.84	3.12	903,576
September 1994	2,270	0.69	239,567	14,028	0.89	2.56	544,042
July 2002	2,920	0.88	308,165	14,593	0.92	1.87	531,950
September 2011	2,180	0.66	230,069	15,834	1.00	1.32	302,755
September 2007	2,740	0.83	289,169	15,834	1.00	1.12	325,276
October 2019 Base case	3,300	1.00	348,269	15,834	1.00	1.00	348,269
Total	-	-	**2,045,289**	-	-	-	**3,710,819**

Table 4: Average expected annual damage reduction

Scale	Probability	Amount of damage (Million JPY)			Average amount of interval damage (Million JPY)	Interval probability	Average annual damage (Million JPY)	Average annual expected damage reduction (Million JPY)
		Without investment	Current river conditions	Benefit				
1/10	0.1000	0	0	0				
					26,177	0.0500	1,309	1,309
1/20	0.0500	65,423	13,070	52,353				
					78,190	0.0167	1,303	2,612
1/30	0.0333	129,996	25,970	104,026				
					191,703	0.0083	1,598	2,901
1/40	0.0250	349,127	69,747	279,380				
					331,525	0.0050	1,658	3,255
1/50	0.0200	479,453	95,783	383,670				
					422,358	0.0033	1,408	3,065
1/60	0.0167	576,146	115,100	461,046				
					493,414	0.0024	1,175	2,583
1/70	0.0143	657,042	131,261	525,781				
					596,378	0.0018	1,065	2,240
1/80	0.0125	833,485	166,510	666,975				
					748,153	0.0025	1,870	2,935
1/100	0.0100	1,036,373	207,042	829,331				
					938,281	0.0033	3,128	**4,998**
1/150	0.0067	1,308,673	261,441	**1,047,232**				

Table 5: Comparison with MLIT's program evaluation (billion JPY (billion USD))

	This study (a)	MLIT estimation (b)	Ratio a/b
Damage by 1/150 flood	1,047 (7.48)	261 (1.86)	4,0
Future benefit	112 (0.8)	31 (0.22)	3.6

4.4 Investment efficiency

The total cost was JPY 626 billion (USD 4.5 billion), compared to the total benefit of JPY 3.81 trillion (USD 27.2 billion), resulting in a benefit-cost ratio of 6.1. Table 6 summarizes the economic analysis.

Table 6: Investment efficiency

Total benefits	JPY 3.81 trillion (USD 27.2 billion)
Total costs	JPY 626 billion yen (USD 4.5 billion)
Benefit-cost ratio B/C	6.1
Net Present Value B-C	JPY 3.2 trillion (USD 22.9 billion)

5. Discussion

The methodology proposed in this study offers a comprehensive approach for evaluating the efficiency of long-term investments in flood protection. Unlike conventional methods that focus on assessing the economic benefits of new projects on a project-by-project basis, this methodology can assess both the accumulated benefits of past investments and the potential benefits of future ones across the entire river basin. By taking a holistic view of the river basin, rather than just individual projects, this methodology offers a more reliable and realistic assessment of the economic impacts of flood protection measures.

A simplified method for estimating flood damage was developed to reduce the computer resources required for flood simulations. This study used a simple linear model of the rate of flood volumes to estimate flood damages reduced by investment. Damage costs in the past should be theoretically estimated separately for all disasters based on flood simulations, which require computer resources. The flood simulation model, which was already developed for detailed project analysis in the Natorigawa River Basin, was used for this study.

The methodology should be simplified further, allowing it to be applied to other river basins—particularly those in developing countries. In addition to computer resources, this model requires hydrological, geographical, and socioeconomic datasets. Other simplified simulation models should be used in developing countries, considering their more limited data and capacity. For example, the rainfall-runoff-inundation model, which can use satellite-based data and requires fewer computer resources than the one employed in this study, may be applicable with data-scarce basins (Bhagabati and Kawasaki 2017).

Developing countries often lack the data necessary to assess disaster damage accurately. In such countries, satellite data can be used for estimating the damage caused by floods and urbanization. The methodology developed for this study used data developed for the economic analysis of flood protection projects in Japan. The government has surveyed damage according to inundation depths and accumulated a dataset to improve the economic analysis of flood protection projects.

The total costs do not include replacing the large structure of dams and gates. Since the analysis period spans 100 years, replacement costs should also be considered. The lifetime of a structure is set at 50 years for asset management in Japan. Currently, no standard methods for estimating the costs of demolishing or renovating dams are available. In addition, determining the lifetime of a dam can be a challenge. Some dams constructed with western technology have functioned well in Japan for over 100 years.

This study focuses only on the flood damage reduction benefits of facilities in river basins. Dams also serve the multipurpose function of supplying water for a variety of uses, including urban consumption and farm irrigation, but these benefits are not included.

As a result of reduced flood damage, investments in flood protection promoted development activities and enhances growth in the Sendai Metropolitan area. In Block R1 in the simulation model, urbanization has progressed due to the construction of new housing. This could be partly due to the public's perception that this low-lying area has become safe due to the flood protection projects.

However, this raises another issue for methodologies like those described here. If urbanization has progressed thanks to flood protection projects, then assets would not have accumulated at the current scale without the projects. The developed methodology may therefore overestimate the benefits of investments since the benefits include reducing damage to assets induced by these investments.

Impacts caused by climate change need to be included to estimate future flood volumes. MLIT projects that rainfall volumes will increase by 10% and flood volumes by 20% throughout the country (Technical Committee on Flood Management Plans Considering Climate Change 2019). These projected figures can be used to develop the methodology further. Furthermore, in developing countries, socioeconomic changes, such as urbanization and population increase, should be considered.

6. Conclusion

While understanding that the efficiency of investments and their contributions to regional socioeconomics is crucial in securing finance for flood protection, such information is rarely available. This study provides a valuable contribution to evidence-based policymaking in investments in flood protection by proposing a methodology for economic analysis of long-term investments in flood protection at the river basin scale. It could provide decision-makers with a more informed basis for prioritizing investments in flood protection and allocating resources effectively. Furthermore, this approach may be applied to other river basins or regions, allowing for the comparison of different investments in flood protection across various geographic locations. The study's methodology represents a significant improvement over conventional project-based economic analyses, which typically evaluate the economic benefits of new projects on a project-by-project basis. Unlike these traditional approaches, the proposed methodology for the assessment of both historical and future benefits takes into account the effects of past urbanization and inflation.

The study used the Natorigawa River basin, including Sendai City, Japan, as a case to demonstrate the proposed methodology. It was found that investments in flood protection over 70 years in the river basin were efficient, with an estimated benefit-cost ratio of 6.1. Structures that have been constructed have prevented Sendai City from flooding several times and will continue to do so in the future. Due to the reduction in flood damage, investments in flood protection have promoted development activities and enhanced growth at the regional level.

This methodology was developed by improving the conventional project-based analysis. However, it still requires computer resources and the datasets of socioeconomics, geography, and hydrology. To apply this methodology in developing countries, methodologies should be simplified further by using satellite data and simple flood simulations, considering their limited capacity and data availability. Damage data by inundation depth for each property type should also be investigated. Future studies should examine the impacts of climate change.

Another limitation of the methodology is that it does not account for the costs of replacing large structures such as dams and gates. These costs should be considered since the analysis period spans 100 years. Although no standard methods for estimating the costs of demolishing or renovating dams are available, future research can explore this issue in greater depth.

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Appendix A

Table: Basic Asset Calculation Quantity

Classification			Data	Unit	Reference	
					Organization	**Year**
Basic Data	**Population**		Population	Person	Statistical information institute for consulting and analysis	2015
	Number of households		Number of households	Household	Statistical information institute for consulting and analysis	2015
	Land use		Rice, paddy field	Km^2	MLIT	2014
General assets	**House**		Floor space	Thousands JPY/km^2	Japan Construction Information Center Foundation	2010
	Household goods		Number of households	Thousands JPY/household	Statistical information institute for consulting and analysis	2015
	Business	**Depreciable assets**	Number of employees	Thousands JPY/person	Statistical information institute for consulting and analysis	2014
		Inventory assets	Number of employees	Thousands JPY/	Statistical information institute for consulting and analysis	2014
Agricultural assets	**Agricultural and fishing**	**Depreciable assets**	Number of agricultural and fishery households	Thousands JPY/household	Statistical information institute for consulting and analysis	2015
		Inventory assets	Number of agricultural and fishery households	Thousands JPY/household	Statistical information institute for consulting and analysis	2015
Agriculture	**Paddy rice**		Paddy field area	Thousands JPY/ha	MLIT	2014
	Crops		Farmland area	Thousands JPY/ha	MLIT	2014

Appendix B

Table: Inundation analysis conditions and property data to be employed

Inundation simulation	**River channel**	Surveyed in 2005	MLIT
	Ground level	100m mesh data in 2008	MLIT
	Land use	Land use data for 1/10th subdivision lots in 2014	MLIT
	Dike、BOX culvert	100m mesh data in 2008	MLIT
Assets	**Population, Number of households**	Census mesh statistics in 2015	Statistical information institute for consulting and analysis
	Number of employees	Economic census of establishments mesh Statistics in 2014.	Statistical information institute for consulting and analysis
	Number of agricultural and fishery households	Census mesh statistics in 2015	Statistical information institute for consulting and analysis
	Floor space	100m mesh floor area data in 2010	Japan Construction Information Center Foundation
	Paddy field area, Farmland area	National land use mesh of land use Numerical Information in 2014	MLIT
	Unit of assets	Asset valuation unit prices and deflators	MLIT

Abstract (in Japanese)

要　約

防災投資は、仙台防災枠組においてその重要性が強調されているように、災害被害を軽減するために必要不可欠なものである。治水事業において新規プロジェクトの経済評価は実施されているものの、流域や地域単位で過去に積み上げてきた投資についての評価はなされていない。治水投資の政策決定に役立つエビデンスを提供するには、地域への発展効果を評価する手法が必要である。本研究では名取川流域をケーススタディとして、流域単位での長期間にわたる治水投資の効果を評価する手法を提案した。名取川流域の約 70 年間の投資は、過去と将来の便益を合わせて、費用便益比が 6.1 と推定され、費用対効果が高いことがわかった。本手法を開発途上国の流域で適用するためには、限られたデータと能力を考慮し、簡素化する必要がある。気候変動による影響、大規模施設の更新コストを考慮することが今後の課題である。

キーワード： 事前防災投資、費用対効果分析、洪水シミュレーション、エビデンスに基づく政策決定