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A Quantitative Analysis of Disaster Risk Reduction Investment Effects for Sustainable Development: Indonesia Case Study

Hiroaki ISHIWATA [#]
Hiroyuki WADA
Pacific Consultants Co., Ltd., Tokyo, Japan

Koji SUZUKI
Makoto IKEDA
Asian Disaster Reduction Center, Kobe, Japan

Naoto TADA
JICA Expert for National Disaster Management Authority in Indonesia

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Abstract: *This paper analyses the long-term impacts of large-scale disasters on the economic growth of developing countries in the Association of Southeast Asian Nations (ASEAN) Community, by the scale of disaster risk reduction (DRR) investments. As a means of quantitatively analysing the optimal level and economic efficiency of DRR investments, a case study was conducted on Indonesia by using a dynamic stochastic macroeconomic model. The results showed that in Indonesia, although greater economic growth is expected when additional DRR investments are made, an excessive DRR investment may contrarily lead to a slowdown in economic growth: an optimal level of DRR investment exists and maintaining its level is essential for sustainable economic growth. Furthermore, it was confirmed that there is a break-even point when the amount of accumulated disaster damage mitigation benefits exceeds the amount of accumulated DRR investment. This demonstrated that the funds invested in DRR could be recovered. Additionally, the results also showed that even if no disaster damage is caused over a long period of time, DRR investments are by no means redundant as the 'ex-ante risk reduction effect' will be generated when the optimal level of DRR investment is made. Lastly, it was determined that providing a continuous DRR investment is important in achieving the global target set forth in the Sendai Framework for Disaster Risk Reduction. In addition, it is considered desirable to maintain a higher level of DRR investment than that which is currently being implemented.*

Keywords: disaster risk reduction investment, catastrophic disaster, dynamic stochastic macroeconomic model, quantitative analysis, Monte Carlo simulation

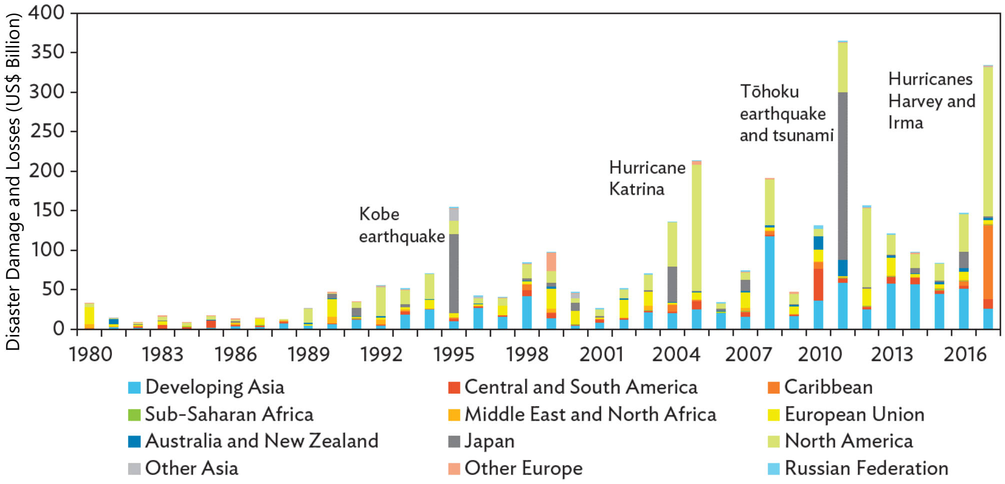
JEL Classification: C61; C68; D58; E13; O11

[#] Corresponding author. Hiroaki Ishiwata. Address: 3-22 Kanda-Nishikicho, Chiyoda-ku, Tokyo 101-8462, JAPAN. E-mail: hiroaki.ishiwata@tk.pacific.co.jp

1. Introduction

In recent years, many large-scale natural disasters have occurred in Asia and have caused a tremendous amount of damage as a result. Such natural disasters include the 2011 earthquake and tsunami off the Pacific coast of Tohoku in Japan, Typhoon Haiyan which hit the Philippines in 2013, as well as the 2018 Sulawesi earthquake and tsunami in Indonesia. Figure 1 shows the damage and losses incurred as a result of disasters around the world. Focusing on the Asian region, it can be understood that several catastrophic disasters, such as those that occurred in 1995 and 2011, happen occasionally in Japan, and the damage and losses incurred from disasters in developing Asian countries are prone to increase year by year.

Figure 1: Global Impact of Disasters

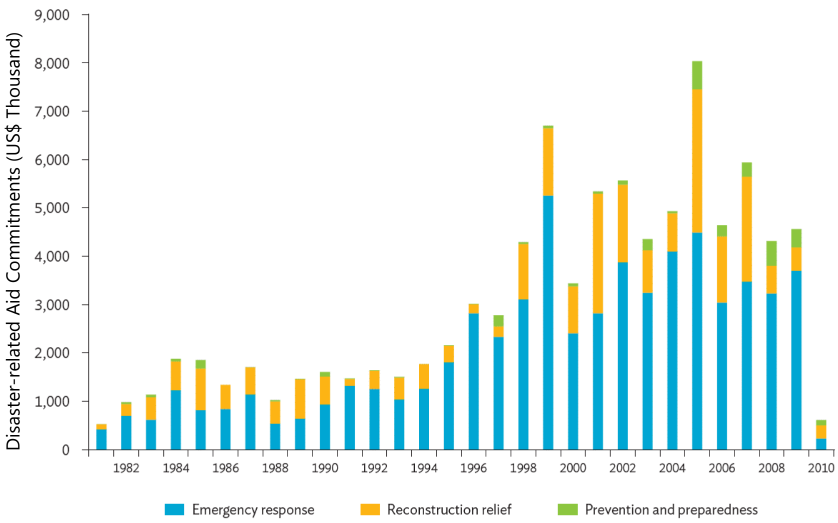


Sources: Dagli and Ferrarini (2019), CRED Database (accessed 1 August 2018).

The damage caused by natural disasters has also been magnified by the fact that disaster risk reduction (DRR) policies have not been adequately implemented in developing countries in particular. Therefore, in order to minimise the 'regret' caused by a disaster, it is important to implement a 'prior investment for DRR,' which is said to be a particularly cost-effective measure that prevents disasters or reduces the damage caused by disasters in advance (UNISDR, 2015). Prior investments for DRR, such as earthquake proofing and building river dikes, can mitigate the disaster damage and losses, reduce the expense for recovery and reconstruction, and increase disaster resilience. The idea behind the 'no regret investment' and the 'low regret investment,' which are aimed towards preventing disasters in advance, is regarded as important by international conferences and international organisations. For example, the 2011 Chengdu Declaration for Action states, ‘DRR was not expenditure but a no-regret investment that could protect lives, property, livelihoods, schools, businesses and employment’ (UNDRR, 2011). In reference to this declaration, the Japan International Cooperation Agency (JICA) also stated that it ‘disseminates a concept of “low regret investment”, which is to make prior investment for DRR according to the assessment of disaster risk and damage in order to make regret as small as possible, instead of allocating budgets for recovery and reconstruction, and to adapt to future environment changes’ (JICA, n.d.).

Although the importance of prior investments for DRR is recognised internationally, the budget allocated for these prior investments is still insufficient in developing countries. Figure 2 shows that prevention and preparedness activities account for only a few percent of disaster-related aid.

Figure 2: Disaster-related Aid Commitments



Sources: Sudo (2019), World Bank (2013).

In the Asian region, during the 7-year period from 2006 to 2012 in Indonesia and the 7-year period from 2005 to 2011 in India, the yearly budget allocated to prior investments for DRR remained at an average of 0.1% of the gross domestic product (GDP) in each respective country (Chakrabarti and Prabodh, 2012; Darwanto, 2012; ESCAP, 2015). On the other hand, Japan, which has faced many large-scale disasters and has had a history of treating DRR measures with high regard, has allocated a yearly budget at an average of 0.7% of their GDP to prior investments for DRR over 55 years spanning 1962 to 2016 (Government of Japan, Cabinet Office; Government of Japan, Ministry of Land, Infrastructure, Transport and Tourism; World Bank).

One of the issues involved in implementing and facilitating DRR investment policies in developing countries, including that of the Association of Southeast Asian Nations (ASEAN) Community, is having the long-term impacts of natural disasters and the importance of DRR investment recognised by policymakers and treasurers in the government, in addition to providing the support needed to make the appropriate decisions. In order to make the appropriate decisions for DRR investment policies, it would be effective to present information that provides answers for questions such as: 'What would be the maximum level of economic development to which the DRR investment is able to generate potentially?; What is the degree of economic development that is expected to be generated reliably from this?; What is the most appropriate proportion of funds that should be allocated to the budget for the DRR investment?'; and 'Can the budget that was invested in DRR be recovered reliably? Moreover, towards improving investment decision-making for DRR, several suggestions are presented for addressing the technical and political challenges: listing economic benefits and costs, listing key stakeholders and distributional economic impacts, and learning from other economic assessments (Vorhies, 2012). The use of economic models is an effective policy support tool to quantitatively present information concerning the optimal level and economic efficiency of the DRR investment.

There have been several past studies on economic models relating to natural disasters, DRR investments, and disaster finance. For example, such models include the analytical framework for the design, pricing, and applications of index-based risk transfer products as a means to handle insurance market imperfections under disaster risks in developing Asian countries (Chantarat et al., 2013), the regression model to show that ex-ante cash transfer programs play a crucial role in encouraging poor households under the threat of disaster in Cambodia to invest in business rather than in food (Vathana et al., 2013), the input–output (I–O) model to examine economic losses and damages caused by natural disasters at the local, national, and the regional levels in the ASEAN region (Shiomi, Ono, and Fukushima, 2019). Moreover, as a useful financial evaluation tool for DRR policies, there is the catastrophe simulation

(CATSIM) model that made it possible to analyse, from the standpoint of financial strategies, the vulnerabilities of a nation's finances when faced with natural disasters (e.g. Mechler et al., 2006), as well as the endogenous business cycle model that made it possible to analyse the long-term impacts of natural disasters on asset formation and production volume (e.g. Hallegatte, Hourcade, and Dumas, 2007; Hallegatte and Ghil, 2008). By looking at the progression in which production capital and DRR capital are formed, a dynamic stochastic macroeconomic model that has made it possible to perform a qualitative analysis on long-term DRR investment policies is also cited (Segi, Ishikura, and Yokomatsu, 2012). Furthermore, in the study conducted by Yokomatsu et al. (2014), human capital was introduced into the dynamic stochastic macroeconomic model, and the quantitative impact of DRR investments on the economic growth and social disparity of developing countries was also displayed. Additionally, by introducing policy variables for DRR investments and the accumulation of DRR capital, the study conducted by Ishiwata and Yokomatsu (2018) was also able to quantitatively determine the optimal level of DRR investment that should be provided, in addition to demonstrating whether there was an 'ex-ante risk reduction effect,' which is an effect that is generated from DRR investments even when no disasters have occurred. However, since the study conducted by Ishiwata and Yokomatsu (2018) was a case study only on Pakistan, which has a history of catastrophic disasters such as floods, earthquakes, and droughts, in addition to having the socio-economic data required for numerical simulations such as the social accounting matrix and the household integrated economic survey, the extent of the ex-ante risk reduction effect that would be generated in other developing countries, such as those in the ASEAN, is still unclear.

The purpose of this research is to analyse the way in which large-scale disasters as well as the presence or absence of DRR investments impact the economic growth of developing countries, including those of the ASEAN Community, on a long-term basis. As a means of quantitatively analysing the optimal level and economic efficiency of DRR investments, a case study was conducted on Indonesia by utilising a dynamic stochastic macroeconomic model that incorporates the idea of DRR. Through this method, the DRR investment policies operate in a quantitative manner, which then allowed us to make proposals for DRR investment policies, which were then analysed. The formulation of the model will be demonstrated in section 2, which will then lead into the deriving of the optimisation conditions in section 3, followed by the case study on Indonesia in section 4. Lastly, the conclusion and recommendations of this research will be outlined in section 5.

2. Model

2.1. Assumptions

The model used in this research is essentially a kind of the Ramsey growth model, which has a discrete time axis (Ramsey, 1928). This model also incorporates the added variables of disaster risk, DRR capital, and household assets. Although the research is based on the model by Ishiwata and Yokomatsu (2018), the model assumes that human capital is a constant variable throughout the calculation period, and it differs from the Ishiwata and Yokomatsu model (2018) in that it takes into account the growth of the population, enhancements in production technology, as well as the disaster damage rates and the depreciation rate of the DRR capital.

The market is regarded as being completely competitive under the assumption that the economic space is a closed real economy that consists of one country that has one sector. Whilst assuming that labour and production capital are necessary components in the production of composite goods, it is also assumed that production is carried out using the remaining factor of production in the event that some of these components are lost due to a disaster. In addition, rapid technological advancements brought about by changes to the socio-economic structure are viewed as unlikely to occur.

The representative household has an infinite time horizon and will undertake economic activities in a completely rational manner with recognition of the disaster risk. Based on the operation of real economics, the household income is treated as being equivalent to the production value, and it is also assumed that a certain percentage of the household income is allocated to DRR investment every year.

Under these assumptions, the model can be described as an Arrow–Debrew economy, which achieves the Pareto-optimal allocation. Therefore, the solution of the central planning problem, in which the representative household allocates all the resources over an infinite time horizon to maximise its expected lifetime utility under its budget constraint, coincides with the solution of the market-oriented problem (Stokey, Lucas, and Prescott, 1989). Following most real business cycle models (Kydland and Prescott, 1982), the analysis is carried out under the framework of a centrally-planned economy where the solution can be generally derived more easily than a market-oriented economy.

2.2. Probability of Disaster Occurrence and the Damage Rate

Assuming that one disaster scale is determined in each period, the probability μ^l of a disaster with a disaster scale of $l \in \{1,2,\cdots,L\}$ occurring is constant regardless of the time, and it also satisfies

$$\sum_l \mu^l = 1.$$

Superscript will be used to indicate the disaster scale l.

There are four types of disaster damage rates: the labour supply damage rate $\omega^l(\cdot)$; the household asset damage rate $\phi^l(\cdot)$; the production capital damage rate $\psi^l(\cdot)$; and the DRR capital damage rate $\sigma^l(\cdot)$. It is assumed that according to the disaster damage mitigation function $\zeta_x(\cdot)$, the disaster damage rates for each disaster scale l will decrease as the DRR capital $g(t)$ accumulates:

$$\begin{aligned}
&\text{Labour supply damage rate:} && \omega^l\big(g(t)\big) = \omega_0^l \cdot \zeta_\omega\big(g(t)\big),\\
&\text{Household asset damage rate:} && \phi^l\big(g(t)\big) = \phi_0^l \cdot \zeta_\phi\big(g(t)\big),\\
&\text{Production capital damage rate:} && \psi^l\big(g(t)\big) = \psi_0^l \cdot \zeta_\psi\big(g(t)\big),\\
&\text{DRR capital damage rate:} && \sigma^l\big(g(t)\big) = \sigma_0^l \cdot \zeta_\sigma\big(g(t)\big)
\end{aligned}$$

for all l, where ω_0^l, ϕ_0^l, ψ_0^l, and σ_0^l respectively indicate the labour supply damage rate, the household asset damage rate, the production capital damage rate, and the DRR capital damage rate in the base year. The functions of the production capital damage rate and the DRR capital damage rate have the modifiers of business continuity plans and insurance markets.

It is assumed that a power function that has DRR capital $g(t)$ as its variable, is used for the disaster damage mitigation function $\zeta_x(\cdot)$:

$$\zeta_x(g(t)) = \left[\frac{g(t)}{g_0}\right]^{-\nu_x}, \qquad x \in \{\omega, \phi, \psi, \sigma\},$$

where ν_x denotes the effect parameter of disaster damage mitigation, whereas g_0 denotes the accumulated DRR capital in the base year.

2.3. Production Technology of Composite Goods

Whilst assuming that the Cobb–Douglas production function $f(\cdot)$ is used for composite goods, it is also assumed that composite goods are produced using the factor of production that remains after a disaster with the disaster scale of l has occurred:

$$f\left(B(t), \hat{h}^l(t), \hat{k}^l(t)\right) = B(t)\left[\hat{h}^l(t)\right]^{\alpha_h}\left[\hat{k}^l(t)\right]^{\alpha_k}$$

for all l, where

$$\begin{aligned} B(t) &= B_0(1+\beta)^{t-t_0}, \\ \hat{h}^l(t) &= \left[1-\omega^l(g(t))\right]\bar{h}, \\ \hat{k}^l(t) &= \left[1-\psi^l(g(t))\right]k(t), \end{aligned}$$

and

$$\sum_{i\in\{h,k\}} \alpha_i = 1, \qquad \alpha_i \in (0,1),$$

where $B(t)$ denotes the total factor productivity (TFP), B_0 denotes the TFP in the base year, β denotes the TFP growth rate, t_0 denotes the base year, and α_i denotes the share parameter of the components of production. Additionally, $\bar{h}$ denotes the human capital and it is assumed that $\bar{h} = 1$.

As with management of domestic economy and finance, GDP $F^l(t)$ is equivalent to the aggregate production value. Therefore, it can be expressed as follows by using the total population $N(t)$:

$$F^l(t) = N(t) \cdot f\left(B(t), \hat{h}^l(t), \hat{k}^l(t)\right)$$

for all l, where

$$N(t) = N_0(1+n)^{t-t_0},$$

where N_0 denotes the total population in the base year, whilst n denotes the population growth rate.

2.4. Economic Activities of a Household

a) Maximising the Expected Lifetime Utility

When faced with disaster risk, the representative household allocates resources in a completely rational manner so as to maximise expected lifetime utility, which is defined by the accumulated amount of non-durable goods consumption $c^l(t)$ and household assets $z(t)$:

$$\mathrm{E}_l\left[\sum_{t'=t}^{\infty} u\left(c^l(t'), \hat{z}^l(t')\right) \cdot \Lambda^{t'-t}\right],$$

where

$$\hat{z}^l(t) = \left[1 - \phi^l\big(g(t)\big)\right] z(t),$$
$$\Lambda = \frac{1}{1+\rho},$$

where $\mathrm{E}_l[\cdot]$ is a symbol that denotes the expectation operator of the disaster scale l. In addition, ρ refers to the time preference rate, whilst Λ refers to the discount factor.

The Stone–Geary utility function, which is able to express the situation in which the investments in each stock are not prioritised and the economic growth is stagnated when the level of consumption is close to the subsistence level of consumption – namely, when the marginal utility of consumption is large – is used as the one-period utility function $u(\cdot)$:

$$u\left(c^l(t), \hat{z}^l(t)\right) = \gamma_c \frac{[c^l(t) - \bar{c}]^{1-\theta_c} - 1}{1 - \theta_c} + \gamma_z \frac{[\hat{z}^l(t)]^{1-\theta_z} - 1}{1 - \theta_z}$$

for all l, where

$$\sum_{j \in \{c,z\}} \gamma_j = 1, \qquad \gamma_j \in (0,1),$$

where γ_j denotes the share parameter of consumption, $\bar{c}$ denotes the minimum subsistence level of consumption, and θ_j denotes the relative risk aversion. When the consumption of non-durable goods $c^l(t)(> \bar{c})$ approaches the minimum subsistence level of consumption$\bar{c}$, the marginal utility $\partial u(\cdot)/\partial c^l(t)$ of the consumption of non-durable goods increases, whilst the level of priority placed on allocating resources to the consumption of non-durable goods $c^l(t)$ is heightened. As a result, there will be a delay in capital formation, which will in turn lead to a slowdown in economic growth.

b) Accumulation of DRR Capital

The DRR capital $g(t)$ serves the role of reducing each of the disaster damage rates. The progression of the accumulation of DRR capital is as follows.

$$g^l(t+1) = (1 - \delta_\sigma - n)\hat{g}^l(t) + d \cdot f\left(B(t), \hat{h}^l(t), \hat{k}^l(t)\right)$$

for all l and d, where

$$\hat{g}^l(t) = \left[1 - \sigma^l\big(g(t)\big)\right] g(t),$$

where δ_σ denotes the depreciation rate of the DRR capital, whilst d denotes the proportion of income that is allocated to the DRR investment. As the DRR capital $g(t)$ decreases at a constant rate $(\delta_\sigma + n)$ every year, only the DRR capital damage rate $\sigma^l(\cdot)$ is worsened due to disasters. However, at the same time, only new DRR investments are accumulated $d \cdot f(\cdot)$. In this model, although the DRR investment rate d is dealt with as a policy variable for the simplicity of calculation, based on the Solow growth model (Solow, 1956), if it is dealt with as an endogenous variable, based on the Ramsey growth model (Ramsey, 1928), the scale of DRR investment $d \cdot f(\cdot)$ could be more linked to market forces, that is, the DRR investment rate d would be larger in developed societies, and smaller in developing societies.

c) *Accumulation of Household Assets*

Household assets $z(t)$ refer to durable goods such as houses and household belongings. The progression of the accumulation of household assets $z(t)$ is as follows.

$$z^l(t+1) = (1 - \delta_z - n)\hat{z}^l(t) + \xi(t)$$

for all l, where δ_z denotes the depreciation rate of household assets, whilst $\xi(t)$ denotes the household asset investment. As the household assets $z(t)$ decrease at a constant rate $(\delta_z + n)$ every year, only the household asset damage rate $\phi^l(\cdot)$ is worsened due to disasters. However, at the same time, the amount of household asset investments $\xi(t)$ is newly accumulated.

d) *Accumulation of Production Capital*

Production capital $k(t)$ refers to infrastructure that is needed in production process, such as production facilities or production equipment. The progression of the accumulation of production capital $k(t)$ is as follows.

$$k^l(t+1) = (1 - \delta_k - n)\hat{k}^l(t) + (1 - d) \cdot f\left(B(t), \hat{h}^l(t), \hat{k}^l(t)\right) - c^l(t) - \xi(t)$$

for all l, where δ_k denotes the depreciation rate of the production capital. As the production capital $k(t)$ decreases at a constant rate $(\delta_k + n)$ every year, only the production capital damage rate $\psi^l(\cdot)$ is worsened due to disasters. Additionally, the formation of production capital $k(t)$ progresses further as the consumption of non-durable goods $c^l(t)$ and household asset investment $\xi(t)$ decreases. This capital formation in turn increases the production volume $f(\cdot)$ of composite goods and stimulates economic growth.

e) Definition of Total Assets

Total assets $a(t)$ is defined as the sum that is derived when household assets $z(t)$ and production capital $k(t)$ are added together.

$$
\begin{aligned}
a^l(t+1) &:= z^l(t+1) + k^l(t+1) \\
&= (1-\delta_z - n)\hat{z}^l(t) + (1-\delta_k - n)\hat{k}^l(t) \\
&\quad + (1-d)\cdot f\left(B(t), \hat{h}^l(t), \hat{k}^l(t)\right) - c^l(t) \\
&= (1-\delta_z - n)\hat{z}^l(t) + (1-\delta_k - n)[\hat{a}^l(t) - \check{z}^l(t)] \\
&\quad + (1-d)\cdot f\left(B(t), \hat{h}^l(t), \hat{a}^l(t) - \check{z}^l(t)\right) - c^l(t)
\end{aligned}
$$

for all l and d, where

$$
\begin{aligned}
\hat{a}^l(t) &= \left[1 - \psi^l\big(g(t)\big)\right] a(t), \\
\check{z}^l(t) &= \left[1 - \psi^l\big(g(t)\big)\right] z(t).
\end{aligned}
$$

By defining total assets $a(t)$, the household asset investment $\xi(t)$, which is one of the control variables, is cancelled out. For this reason, household assets $z(t)$, which is a state variable, as a control variable with respect to the total assets $a(t)$ can be treated; thus, making it convenient when calculations are made.

3) Dynamic Optimisation

3.1. Flow of Events

The assumed flow of events in year t is as follows.

i) At the beginning of year t, the representative household confirms the accumulated amount of total assets $a(t)$ and DRR capital $g(t)$, along with the TFP $B(t)$, and the level of the DRR investment ratio d.

ii) For the ex-ante problem, the representative household determines the level of holding for household assets $z(t)$ in the year t in order to maximise the expected lifetime utility, of which the maximisation is achieved by the optimal allocation of consumption and investments in each stock throughout present and future periods, when faced with a disaster risk. In addition, the level of holding for production capital $k(t) = a(t) - z(t)$ is also determined through this.

iii) A disaster with a disaster scale of l occurs, leading to a loss in each type of capital, which corresponds to disaster damage rates. Household assets $z(t)$, production capital $k(t)$, and DRR capital $g(t)$ will be subjected to continued multiplicative shocks, whilst the labour supply $\bar{h}$ will be subjected to temporary multiplicative shocks.

iv) For the ex-post problem, composite goods will be produced from the remaining components of production, whilst the representative household goes on to earn an income $f(\cdot)$. A portion of this income will be allocated to the DRR investment $d \cdot f(\cdot)$. At the same time, the consumption of non-durable goods $c^l(t)$ will be determined, alongside the instant utility level $u(\cdot)$.

v) At the end of year t, the total assets $a^l(t+1)$ of year $t+1$, the DRR capital $g^l(t+1)$, as well as the TFP $B(t+1)$ will be determined. Afterwards, the same cycle will be repeated from i).

3.2. Value Function

The representative household's issue with dynamic optimisation is described as follows by using the value function $V(\cdot)$ under the constraints of the formation of each type of capital.

$$V(a(t), g(t), B(t), d) = \max \ \mathrm{E}_l\left[\sum_{t'=t}^{\infty} u\left(c^l\left(t'\right), \hat{z}^l\left(t'\right)\right) \cdot \Lambda^{t'-t}\right],$$

s.t.

$$\begin{aligned}
a^l(t+1) = (1-\delta_z-n)\hat{z}^l(t) + (1-\delta_k-n)[\hat{a}^l(t) - \check{z}^l(t)] \\
+ (1-d) \cdot f\left(B(t), \hat{h}^l(t), \hat{a}^l(t) - \check{z}^l(t)\right) - c^l(t),
\end{aligned}$$

$$g^l(t+1) = (1-\delta_\sigma-n)\hat{g}(t) + d \cdot f\left(B(t), \hat{h}^l(t), \hat{a}^l(t) - \check{z}^l(t)\right),$$

$$a^l(t+1),\ g^l(t+1) > 0$$

for all l and d. The value function $V(\cdot)$ can be regarded as an index of social welfare as it is the maximum value of the expected utility function that can be achieved through the optimal allocation of resources.

The equation above is equivalent to the Bellman equation (Bellman, 1957) shown below, which is a recursive equation:

$$\begin{aligned}
&V(a(t), g(t), B(t), d) \\
&\quad = \max_{c^l(t),\, z(t)} \mathrm{E}_l\left[u\left(c^l(t), \hat{z}^l(t)\right) + \Lambda \cdot V(a^l(t+1), g^l(t+1), B(t+1), d)\right] \\
&\quad\quad = \max_{c^l(t),\, z(t)} \sum_l \mu^l \left[u\left(c^l(t), \hat{z}^l(t)\right) + \Lambda \right. \\
&\quad\quad\quad \left. \cdot V(a^l(t+1), g^l(t+1), B(t+1), d)\right].
\end{aligned}$$

3.3. Optimal Conditions

The first-order conditions for the consumption of non-durable goods $c^l(t)$ and household assets $z(t)$, with regards to the value function $V(\cdot)$ described by the Bellman equation, is as follows.

$$c^l(t):\ u_c^l(t) = \Lambda \cdot V_a^l(t+1) \qquad \text{for all } l,$$

$$z(t):\ \sum_l \mu^l \left[u_z^l(t) + \Lambda \cdot \left\{V_a^l(t+1) \cdot \frac{\partial a^l(t+1)}{\partial z(t)} + V_g^l(t+1) \cdot \frac{\partial g^l(t+1)}{\partial z(t)}\right\}\right] = 0,$$

where

$$V_a^l(t+1) = \frac{\partial V(a^l(t+1), g^l(t+1), B(t+1), d)}{\partial a^l(t+1)},$$
$$V_g^l(t+1) = \frac{\partial V(a^l(t+1), g^l(t+1), B(t+1), d)}{\partial g^l(t+1)},$$
$$u_c^l(t) = \frac{\partial u\left(c^l(t), \hat{z}^l(t)\right)}{\partial c^l(t)},$$
$$u_z^l(t) = \frac{\partial u\left(c^l(t), \hat{z}^l(t)\right)}{\partial z(t)}$$

for all d. The first-order conditions for the consumption of non-durable goods $c^l(t)$ show that the marginal utility of the consumption of non-durable goods $c^l(t)$ is equivalent to the marginal value of the present discount factor for total assets $a(t)$.

The transversality conditions, which are the complementary conditions for the end of a period, are as follows.

$$\lim_{t\to\infty} a(t) \cdot \frac{\partial V(a(t), g(t), B(t), d)}{\partial a(t)} \cdot \Lambda^t = 0,$$
$$\lim_{t\to\infty} g(t) \cdot \frac{\partial V(a(t), g(t), B(t), d)}{\partial g(t)} \cdot \Lambda^t = 0 \quad \text{for all } d.$$

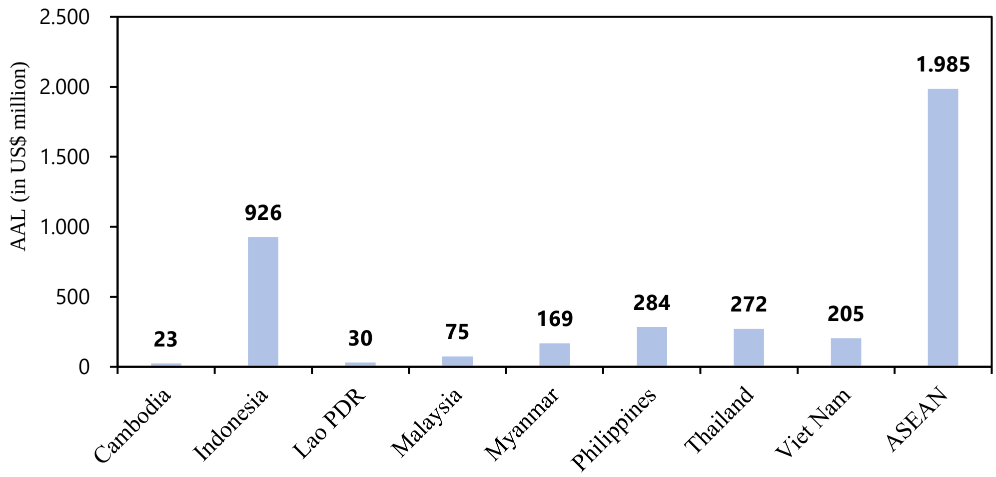
In this research, the value function expressed by the Bellman equation is used as an objective function. Under the constraints of the formation of each type of capital, this objective function is then solved via a numerical simulation method called Value Function Iteration (e.g. Heer and Maußner, 2008), which allows us to numerically obtain the socially optimal solution.

4. Case Study: Effects of DRR Investments in Indonesia

4.1. Prerequisites of the Setting

A case study was conducted in Indonesia to demonstrate quantitatively that DRR investments are indispensable to the economic and social development of developing countries, including those of the ASEAN Community. Indonesia has the largest average annual loss amongst the ASEAN Community, as shown in Figure 3, and also often faces catastrophic disasters such as the 2004 Indian Ocean and the 2018 Sulawesi earthquake and tsunami. With 2003 as its base year, the case study was conducted over a total estimated period of 28 years spanning 2003 to 2030. Furthermore, economic growth was calculated on a yearly interval.

Figure 3: Average Annual Loss for Different Countries and the ASEAN Region, 1970 to 2009



AAL = average annual loss, ASEAN = Association of Southeast Asian Nations.
Source: Adapted from Gupta (2010).

The parameter values used in this case study are listed in Tables A1 and A2 (see Appendix). Some of the parameter values were set using assumed values due to the restrictions on matters such as the amount of data that can be stored in Indonesia. For example, for the effect parameter of disaster damage mitigation ν_x in the disaster damage mitigation function $\zeta_x(\cdot)$, estimates from data such as flood damage statistics and social capital stock figures, etc. in Japan for the period between 1953 and 2014 were used, since there was only around 10 years' worth of data for that period in Indonesia and precisely estimating the function was difficult. These assumed values will need to be replaced in the future once data has been accumulated for the country where the case study is conducted.

Data on the socio-economics of Indonesia was mainly sourced from the 2003 Social Accounting Matrix created by Yusuf (2006), as well as the World Development Indicators, which is the statistics database of the World Bank. Using this data, the initial value of each state variable and calibrated parameter value in the base year was established.

Data on the disaster damage in Indonesia was sourced from disaster statistics by the Indonesian National Agency for Disaster Countermeasure (BNPB). However, given inadequacies in the data accuracy of older disaster damage data sets, each disaster damage rate was estimated using data from 2002 to 2016, which is the period of 15 years where a relatively large amount of data on disaster damage was recorded. Out of all the natural disasters that occurred during the aforementioned period, flood damage (floods, tsunamis,[1] storm surges, landslides) made up around 61.1% of the number of disaster records. Flood damage was also the reason for around 99.3% of the economic loss sustained, and it was attributable for a majority of around 79.5% of the number of disaster victims (dead, injured, missing, evacuees, and those affected by disasters) (according to the disaster statistics provided by BNPB). For these reasons, 'flood damage' was chosen as the disaster to be covered in the case study. In this case study, the disaster damage rates for each type of capital is classified into five ranks, whereby disaster scale $l = 1$ is defined as the lowest level of disaster damage, and disaster scale $l = 5$ is defined as the highest level of disaster damage. However, as there is only a small number of inter-annual disaster records that can be used to estimate the disaster damage rates by disaster scales, the average value for the amount of damage sustained each year from disasters is assumed to be Rp30 trillion (BNPB, 2016), which is the figure that was published by the BNPB in Indonesia. Subsequently, this average value along with the data on disaster damage for each year is used to derive the standard deviation of the amount of disaster damage sustained. Following this, the disaster damage rates for each disaster scale is then determined by looking at

[1]It is important to note that the damage caused by the 2004 Indian Ocean earthquake, which struck off the coast of Sumatra, is recorded as the sum of the damages sustained from both the tsunami and earthquake. Therefore, the figure for the damage caused by the tsunami also incorporates the damage caused by the earthquake.

the discrepancies with the average value. These disaster damage rates will need to be improved in the future once data has been accumulated and must be accurate for the country where the case study is conducted – in this case, Indonesia. Although the set values of the disaster damage rates are not 0% for the disaster scale $l = 1$, the values are still very small. Therefore, in this case study, the disasters with a disaster scale of $l = 1$ are treated as cases where no disaster has occurred.

In the analysis of the DRR investment policy, eight cases with differing DRR investment levels d are considered. Specifically, these cases have the respective DRR investment levels of $d = 0.0\%$, 0.1%, 0.3%, 0.5%, 0.7%, 1.0%, 2.0%, and 3.0%. The current DRR investment level d_0 is 0.1%, which is the average value of the DRR investment levels for the 7-year period spanning from 2006 to 2012 (Chakrabarti and Prabodh, 2012; Darwanto, 2012; ESCAP, 2015). Additionally, the DRR investment level for cases where there is no DRR investment (without a case) d_{wo} is 0.0%.

4.2. Confirming the Reproducibility of Current Conditions

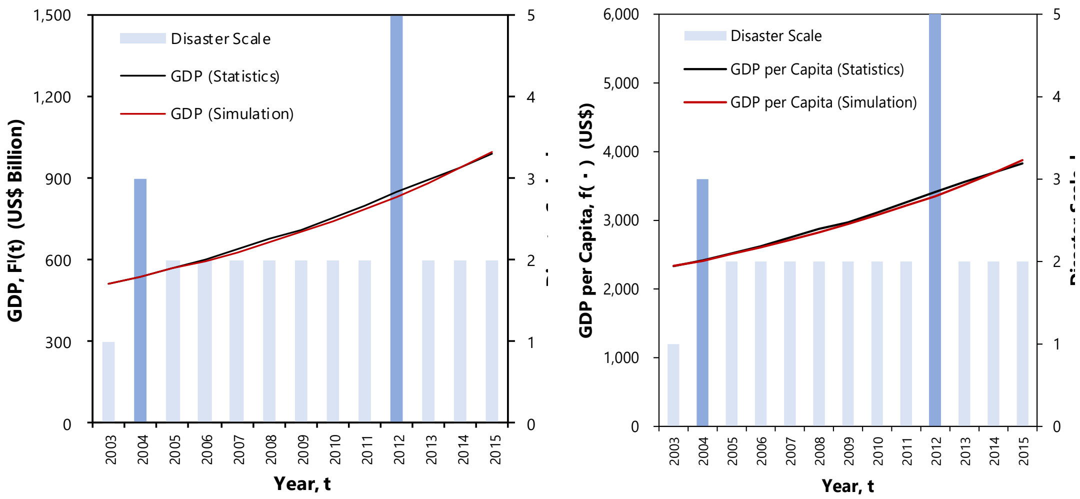
Firstly, in order to confirm the model's reproducibility of current conditions, the statistics from the World Bank with the GDP and GDP per capita from the case study results that were obtained through the use of this model were compared. The period for the reproduction of current conditions spans 13 years from the base year of 2003 to 2015. Additionally, the disaster scale l that most closely reflects the actual circumstances was used to describe the disasters in each year. 2004 and 2012, in particular, are recorded as years in which a significant amount of damage was caused by the Indian Ocean earthquake and tsunami and the Sumatra flood, respectively (according to BNPB disaster statistics). Therefore, the disaster scale l for these 2 years is greater than that of other years.

Figure 4 shows the results of the reproduction of current conditions. Looking at Figure 4 (A), statistics show that the GDP grew by 1.92 times over the 13-year period that begins from the base year, whilst the results of the case study show that the GDP grew by 1.94 times over the same period. Furthermore, the year that had the largest discrepancy with the statistics was 2012, where there was a discrepancy of –2.34%. Looking at Figure 4 (B), statistics show that the GDP per capita grew by 1.64 times over the 13-year period that begins from the base year, whilst the results of the case study show that the GDP per capita grew by 1.66 times over the same period.

Furthermore, the year that had the largest discrepancy with the statistics was 2012, where there was a discrepancy of –1.89%. From these comparisons, it was able to be confirmed that the case study results, which were obtained through the use of this model, demonstrate that it is possible for the current conditions to be reproduced.

Figure 4: Comparison between Statistics and Results of Case Study

(A) GDP, $F^l(t)$ **(B) GDP per Capita, $f(\cdot)$**



GDP = gross domestic product.
Sources: World Development Indicators (World Bank), and the case study results of the model in this paper (see Appendix for detailed input data).

4.3. Analysis on the Optimal Level of DRR Investment

In addition to quantitatively analysing the long-term impacts of disaster damage on the growth progression of each variable for each DRR investment policy, the optimal DRR investment policy d will also be presented. Calculations will be made over 28 years, spanning from the base year of 2003 to 2030. In the same way that current conditions are reproduced, 10,000 Monte Carlo simulations of disasters with the disaster scale l that most closely reflects the actual disaster damage rates in each year between 2003 and 2015, along with disasters with a disaster scale l that is randomly selected according to the probability of occurrence μ^l for each disaster scale between 2016 and 2030, will be regularly conducted.

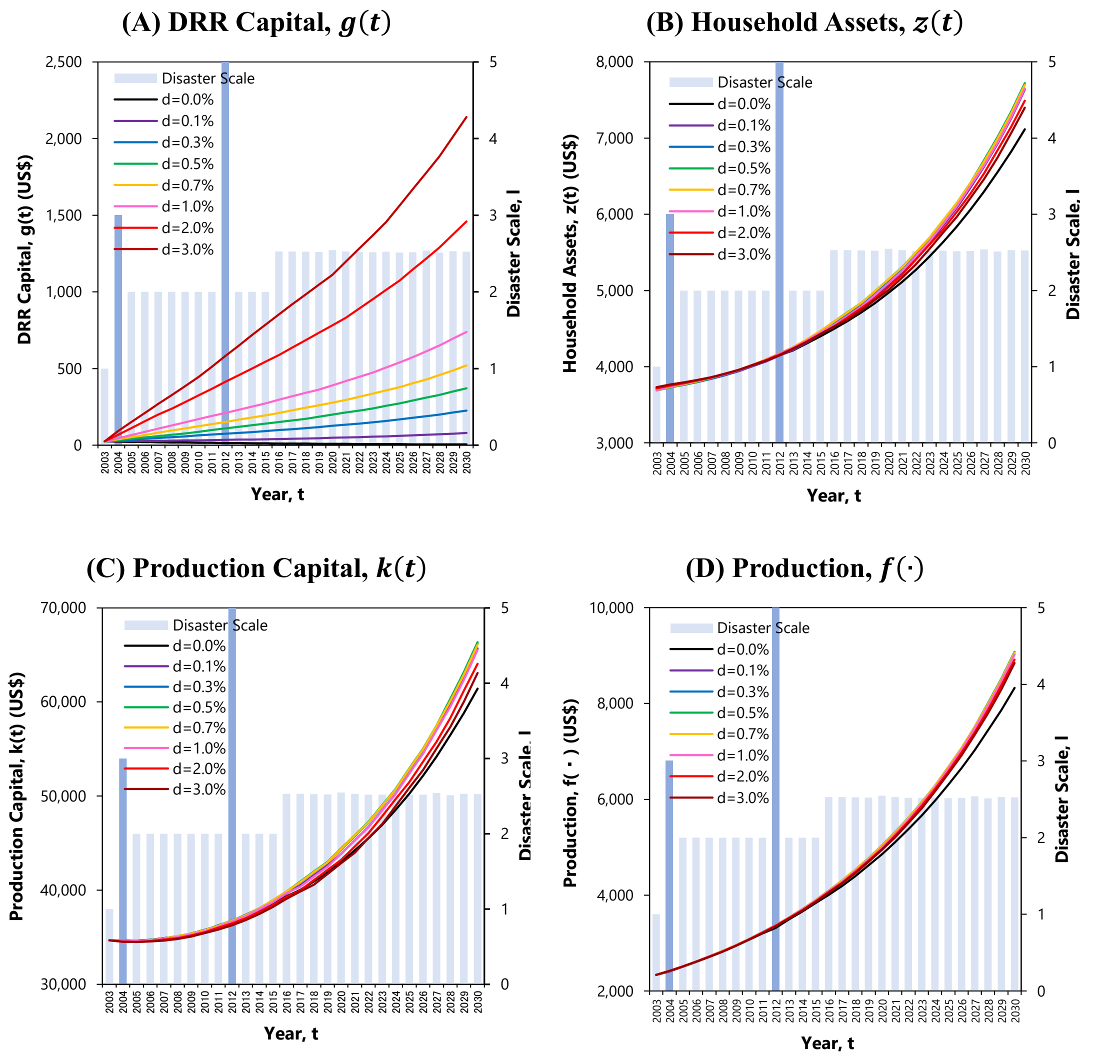
Figure 5 (A) shows the progression behind the formation of DRR capital $g(t)$. The formation of DRR capital $g(t)$ is greater when a policy with a high level of DRR investment d is implemented, as opposed to a policy with a low level of DRR investment. In addition, it can be seen that the gap between the DRR capital for each disaster scale tends to widen every year.

Table 1: GDP Growth Rate by DRR Policy

DRR Policy (% of GDP)	GDP Growth Rate: 28-Year Period Growth	GDP Growth Rate: Annual Average Growth	Growth under Catastrophic Disaster: in 2004	Growth under Catastrophic Disaster: in 2012
$d = 0.0$	4.06	6.19%	4.43%	4.89%
$d = 0.1$	4.48	6.50%	4.52%	5.60%
$d = 0.3$	4.51	6.52%	4.65%	5.79%
$d = 0.5$	4.51	6.53%	4.71%	5.93%
$d = 0.7$	4.50	6.52%	4.80%	5.96%
$d = 1.0$	4.48	6.50%	4.87%	5.98%
$d = 2.0$	4.41	6.46%	4.87%	5.85%
$d = 3.0$	4.37	6.42%	4.94%	5.86%

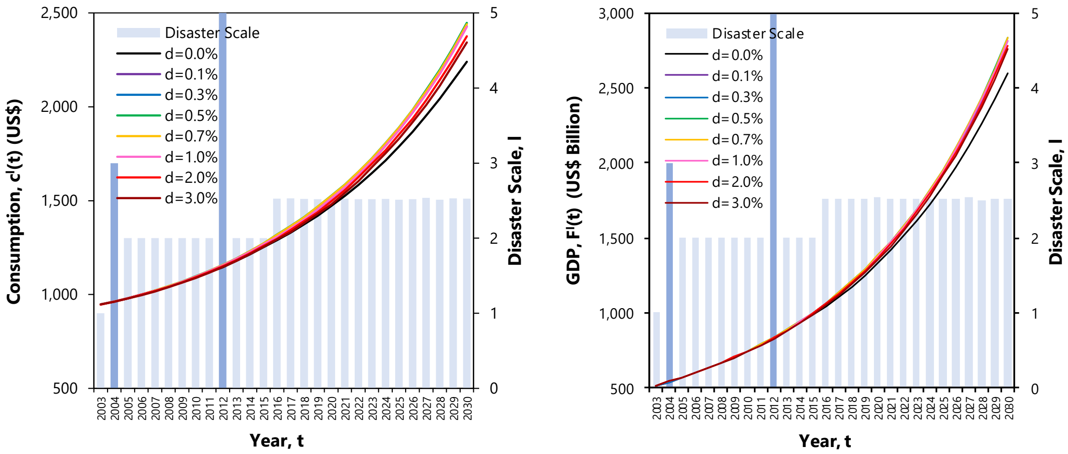
DRR = disaster risk reduction, GDP = gross domestic product.
Source: From the case study results of the model in this paper (see Appendix for detailed input data).

Figure 5: Analysis of Optimal DRR Policy



(E) Consumption, $c^l(t)$

(F) GDP, $F^l(t)$



DRR = disaster risk reduction, GDP = gross domestic product.
Source: from the case study results of the model in this paper (see Appendix for detailed input data).

Figure 5 (B) to Figure 5 (E) respectively show the progression behind the growth of household assets $z(t)$, production capital $k(t)$, production volume $f(\cdot)$, and the consumption of non-durable goods $c^l(t)$. By looking at the values for 2030, it can be confirmed that each variable grows the most with the 0.5%-Policy. This is attributable to the fact that by accumulating DRR capital $g(t)$ to reduce the loss of household assets $z(t)$ caused by disasters, the increase in the marginal utility $u_z^l(t)$ of household assets is suppressed, in addition to reducing the loss of production capital $k(t)$ caused by disasters. This thereby leads to the formation of production capital $k(t)$, which in turn leads to an increase in production volume $f(\cdot)$, or an increase in income, to be exact. Then, an increase in the consumption of non-durable goods $c^l(t)$ can be seen. On the other hand, in the case of the 0.0%-Policy where the DRR investment is far too insufficient, a significant amount of each type of capital is lost after a disaster occurs. In addition, there is also an increase in the marginal utility $u_c^l(t)$ of the consumption of non-durable goods, which delays the formation of production capital $k(t)$, and consequently leads to a slowdown in economic growth. Although the disaster damage of each type of capital is reduced in the case of the 3.0%-Policy, in which the DRR investment is excessive, the 3.0%-Policy also leads to a slowdown in economic growth, as investing in production capital is more efficient than investing in the DRR investment from the standpoint of economic growth.

Figure 5 (F) shows the progression behind the growth of GDP, $F^l(t)$, and Table 1 shows the GDP growth rate by DRR Policy. By looking at the values for 2030, it can be seen that the optimal DRR investment level d is the 0.5%-Policy, which is the same for each variable. Looking at the data across the total period of 28 years spanning from 2003 to 2030, it can be seen that the GDP is growing by 4.06 times (6.19% per year on average) with the 0.0%-Policy where there is no DRR investment. It could also be surmised that the GDP is growing by 4.48 times (6.50% per year on average) with the current 0.1%-Policy, and growing by 4.51 times (6.53% per year on average) with the optimal 0.5%-Policy. Therefore, it is expected that economic growth could be achieved by making additional DRR investments. There is no significant difference in growth between the current 0.1%-Policy and the optimal 0.5%-Policy. However, by looking at the data between 2004 and 2012 where major disasters occurred, it can be seen that the optimal 0.5%-Policy is achieving higher economic growth with growth rates of 0.33% than the current 0.1%-Policy which is that of 0.19%. Therefore, it can be inferred that in the sample path where a disaster scale of $l = 5$ occurs frequently, the difference in growth will widen even further with the growth in the optimal 0.5%-Policy being higher than that of the current 0.1%-Policy.

These results show that in Indonesia, whilst additional DRR investments are expected to generate further economic growth, over-investment may actually cause a slow-down in economic growth. Therefore, it is important to maintain the optimum level of DRR investment, which is around the level of the 0.5%-Policy. Furthermore, by looking at the growth progression of each variable for each DRR investment policy, although there are no major differences in short terms of less than 3 years, there are, however, major differences in longer terms of more than 10 years.

4.4. Analysis on the Economic Efficiency of DRR Investments

a) Break-even Analysis Based on the Amount of Accumulated DRR Investments and the Amount of Accumulated Disaster Damage Mitigation

In order to analyse the economic efficiency of DRR investments, the number of years required to recover the amount invested for the DRR budget by comparing the amount of accumulated DRR investments $TI(d,t)$ to the amount of accumulated disaster damage mitigation $TM(d,t)$ are estimated. Here, the amount of accumulated DRR investments $TI(d,t)$ and the amount of accumulated damage mitigation $TM(d,t)$ are respectively defined as follows, whilst the year with the result showing $TM(d,t) > TI(d,t)$ is considered the break-even year.

$$TI(d,t) := \mathrm{E}_\iota\left[\sum_{t' \le t}\left\{d \cdot f^\iota\left(d,t'\right) - d_{wo} \cdot f^\iota\left(d_{wo},t'\right)\right\}\right],$$

$$TM(d,t) := \mathrm{E}_\iota\left[\sum_{t' \le t}\left\{DDEL^\iota\left(d_{wo},t'\right) - DDEL^\iota\left(d,t'\right)\right\}\right]$$

for all d, where

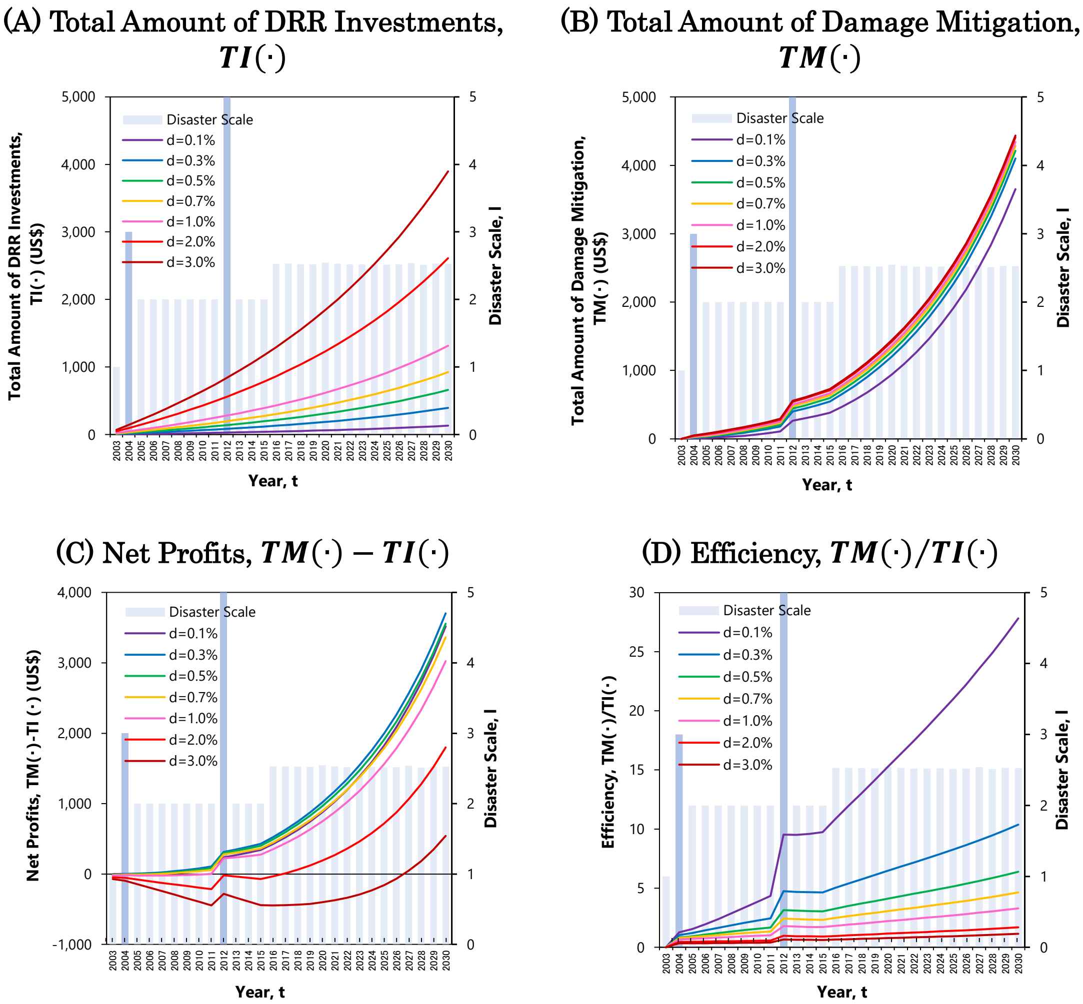
$$DDEL^\iota(d,t) := \sigma^l\left(g^\iota(d,t)\right) \cdot g^\iota(d,t) + \phi^l\left(g^\iota(d,t)\right) \cdot z^\iota(d,t) + \psi^l\left(g^\iota(d,t)\right) \cdot k^\iota(d,t)$$

for all l, where $\mathrm{E}_\iota[\cdot]$ denotes the expectation operator of the conducted number ι for Monte Carlo simulation. $DDEL^\iota(d,t)$ is defined as the total amount of direct economic loss in the year t, when the DRR investment level of d was selected.

Figure 6 (A) is a graph that shows the amount of accumulated DRR investments $TI(d,t)$, whilst Figure 6 (B) is a graph that shows the amount of accumulated damage mitigation $TM(d,t)$. From the two graphs, it can be confirmed that there is a proportional relationship between the amount of accumulated DRR investments $TI(d,t)$ and the amount of accumulated damage mitigation $TM(d,t)$.

Figure 6 (C) shows the net profits $TM(d,t) - TI(d,t)$ of DRR investments, whilst Figure 6 (D) shows the efficiency of DRR investments $TM(d,t)/TI(d,t)$. By looking at the values for 2030, it can be confirmed that there was a net profit of US$3,520 for the current 0.1%-Policy (preventing a direct economic loss of US$27.7 on average for every US$1 of DRR investment), a net profit of US$3,704 for the most efficient 0.3%-Policy (preventing a direct economic loss of US$10.4 on average for every US$1 of DRR investment), as well as a net profit of US$542 for the 3.0%-Policy where there is an over-investment (preventing a direct economic loss of US$1.1 on average for every US$1 of DRR investment). From these results, it can be seen that in the case of the current 0.1%-Policy, a greater budget should be allocated for DRR investments, seeing that DRR investments are highly efficient. In the case of the 3.0%-Policy, in which there is an over-investment, it takes time to recover the funds invested and a net loss is expected for more than 20 years. However, in the long term, an improvement will be seen as it will be possible to obtain a net profit in 2027 (after 25 years).

Figure 6: Break-even Analysis of DRR Investments



DRR = disaster risk reduction.

Source: From the case study results of the model in this paper (see Appendix for detailed input data).

Table 2: Break-even Year (Period), Net Profits, and Efficiency of DRR Investments

DRR Policy (% of GDP)	Break-even Year (Period)	Net Profits, $TM(\cdot) - TI(\cdot)$	Efficiency, $TM(\cdot)/TI(\cdot)$
d = 0.1	t = 2004 (2 Period)	3,520 (US$)	27.8
d = 0.3	t = 2004 (2 Period)	3,704 (US$)	10.4
d = 0.5	t = 2006 (4 Period)	3,555 (US$)	6.4
d = 0.7	t = 2007 (5 Period)	3,363 (US$)	4.6
d = 1.0	t = 2011 (9 Period)	3,026 (US$)	3.3
d = 2.0	t = 2017 (15 Period)	1,801 (US$)	1.7
d = 3.0	t = 2027 (25 Period)	542 (US$)	1.1

DRR = disaster risk reduction, GDP = gross domestic product,
TM = total amount of damage mitigation, TI = total amount of DRR investments.
Source: From the case study results of the model in this paper (see Appendix for detailed input data).

From these results, for Indonesia, the break-even year of a DRR investment is reached at a relatively early stage, so long as the investment is not excessive. In particular, when the major disasters of 2004 and 2012 occurred, it was found that the net profit increased rapidly and continues to increase year by year. DRR investments prevent direct economic losses to each asset as a result of disasters and also make it possible to sustain the level of production after disasters have occurred. Furthermore, DRR investments have long-term effects once invested. Based on these findings, it can be said that DRR investments are reasonable investments in the long term.

b) Estimating the Ex-ante Risk Reduction Effect of DRR Investments

The ex-ante risk reduction effect $ARRE(d, t)$ is an actual effect that can be generated by a DRR investment, even when no disasters occur. For example, the fact that flood risks are mitigated by investments in river dikes induces the agglomeration of production facilities, accelerating economic growth. Thus, the guarantee that the ARRE can certainly be attained regardless of whether disasters actually occur makes DRR investments, namely 'low regret or no regret investments' to DRR facilities, more implementable.

Here, the DRR investment effect $DRRE(d, t)$ is separated into two categories, that is, the ex-ante risk reduction effect $ARRE(d, t)$ and the ex-post damage mitigation effect $PDME(d, t)$.

$$\begin{aligned}
DRRE(d,t) &:= MP(d,t) - MP(d_{wo},t) \\
&= NDP(d,t) - NDP(d_{wo},t) \\
&\quad + \mathrm{E}_\iota\left[\sum_{t' \le t}\left\{D^\iota\left(l^\iota(t'), d_{wo}\right) - D^\iota\left(l^\iota(t'), d\right)\right\}\right] \\
&= ARRE(d,t) + PDME(d,t)
\end{aligned}$$

for all d, where

$$\begin{aligned}
ARRE(d,t) &:= NDP(d,t) - NDP(d_{wo},t), \\
PDME(d,t) &:= \mathrm{E}_\iota\left[\sum_{t' \le t}\left\{D^\iota\left(l^\iota\left(t'\right), d_{wo}\right) - D^\iota\left(l^\iota\left(t'\right), d\right)\right\}\right],
\end{aligned}$$

and

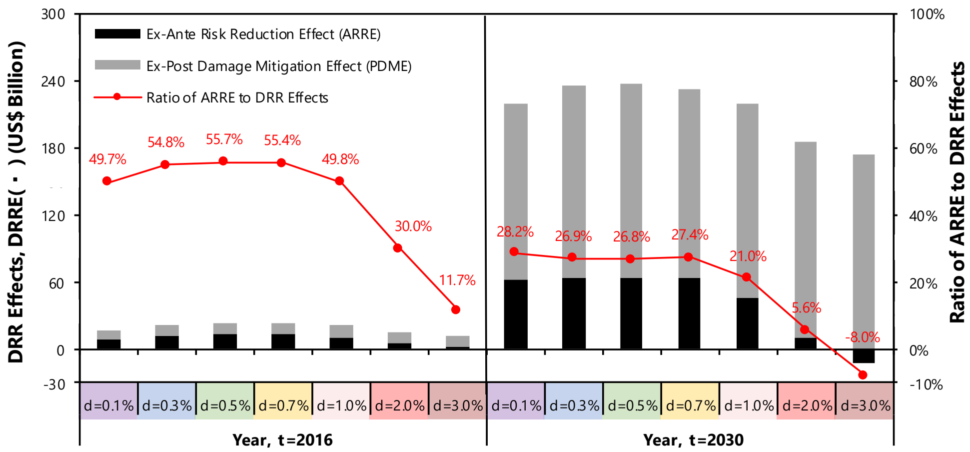
$$\begin{aligned}
MP(d,t) &:= \mathrm{E}_\iota[SP^\iota(d,t)], \\
SP^\iota(d,t) &:= NDP(d,t) - \sum_{t' \le t} D^\iota\left(l^\iota(t'), d\right),
\end{aligned}$$

where $MP(d,t)$, $NDP(d,t)$, and $SP^\iota(d,t)$ respectively denote the expected path, the path where no disaster has occurred, and the sample path of the conducted number ι for Monte Carlo simulation. $D^\iota(d,t)$ is the GDP loss that was caused by a disaster with the disaster scale of l during the year t.

Figure 7 shows the magnitude of the DRR investment effect $DRRE(d,t)$ in 2016 and 2030, along with the breakdown for it. In both years, the 0.5%-Policy more or less has the largest DRR investment effect $DRRE(d,t)$, and this effect tends to increase with time. Looking at the percentages that are attributable to the ex-ante risk reduction effect $ARRE(d,t)$, it can be seen that for the optimal 0.5%-Policy, the ex-ante risk reduction effect $ARRE(d,t)$ accounted for a substantial 55.7% of the DRR effect $DRRE(d,t)$ in 2016 and 26.8% in 2030. In other words, seeing that the ex-ante risk reduction effect $ARRE(d,t)$ cannot be derived from the use of past models, which do not incorporate stochastic optimisation, it is assumed that the amount of ex-ante risk reduction effect $ARRE(d,t)$ is underestimated for the DRR investment effect $DRRE(d,t)$. However, when looking at the value for the 3.0%-Policy in 2030, in which there is an over-investment, it can be seen that the value for the ex-ante risk reduction effect $ARRE(d,t)$ is negative. This means that excessive DRR investments hinder the budget allocation for other types of capital, which leads to economic growth as a result. Amongst the values found in the DRR investment effect $DRRE(d,t)$, there is a tendency for the ex-post damage mitigation effect $PDME(d,t)$ to increase in proportion to the DRR investment level d.

From these results, the existence of the ex-ante risk reduction effect $ARRE(d,t)$ in Indonesia could be confirmed. Therefore, it was understood that DRR investments contribute to economic growth even if no disasters have occurred. In short, it can be said that DRR investments are not futile as long as they are not excessive, namely the ARRE is weakened due to the large cost of DRR investments that interrupt the investments in production facilities and decrease the production of composite goods, deaccelerating economic growth.

Figure 7: Scale and Ratio of ARRE to DRRE



ARRE = ex-ante risk reduction effect, DRR = disaster risk reduction, DRRE = DRR investment effect.
Source: From the case study results of the model in this paper (see Appendix for detailed input data).

4.5. Analysis on the Achievement of the Global Target

As part of this study, the year in which the global target specified in the 'Sendai Framework for Disaster Risk Reduction 2015–2030' would be achieved is predicted. This target is called 'Global Target 3: Reduce direct disaster economic loss in relation to global gross domestic product (GDP) by 2030' (UNISDR, 2015). Firstly, the following shows the definition of the indicator $SFDRR(d,t)$ in this paper, which compares the values for 2015 with the direct economic loss caused by natural disasters that is expressed as a percentage of the GDP. In addition, the year with the result showing $SFDRR(d,t) < 100\%$ is also considered the year in which the target is achieved.

$$SFDRR(d,t):$$
$$= \mathrm{E}_{\iota}\left[\frac{N(t)\cdot DDEL^{\iota}(d,t)}{F_{\iota}^{l}(d,t)}\Big/\frac{N(2015)\cdot DDEL^{\iota}(d,2015)}{F_{\iota}^{l}(d,2015)}\right] \quad \text{for all } l \text{ and } d.$$

By looking at Figure 8, which is a graph of the above indicator, as well as Table 3, which shows the year in which the goal is achieved according to the DRR investment policy, it can be seen that the target is expected to be achieved in around 2024 under the current 0.1%-Policy. In addition, the target is expected to be achieved in 2022 under the 0.3%-Policy as well as other policies for DRR investment levels greater than this. However, in the case of the 0.0%-Policy (without case), in which no DRR investment is made, it is not expected that the target will be achieved.

From these results, it can be said that in Indonesia, providing continuous DRR investments is important in achieving ‘Global Target 3’, which is to reduce direct disaster-related economic loss in relation to global GDP by 2030, namely focusing on economic losses incurred by the disaster, differing from the other targets that focus on disaster mortality, affected people, damage to critical infrastructure, DRR strategies, international cooperation, and opportunities to access disaster risk information, in the ‘Sendai Framework for Disaster Risk Reduction 2015–2030.’ Furthermore, it would also be desirable to maintain a DRR investment level that is higher than the current level.

Figure 8: Index of Ratio of Direct Disaster Economic Loss to GDP, $SFDRR(\cdot)$

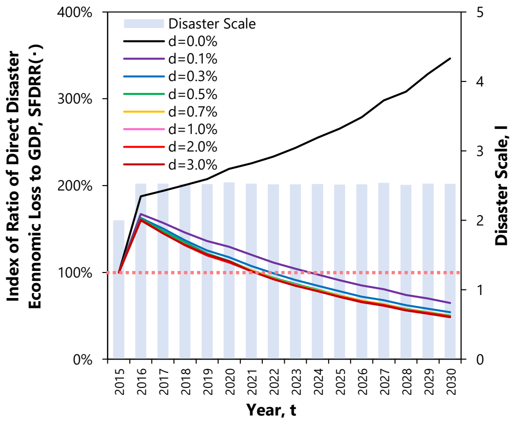


Table 3: Expected Achievement Year of Global Target 3 on SFDRR

DRR Policy (% of GDP)	Expected Achievement Year of SFDRR Target 3
$d = 0.0$	—
$d = 0.1$	$t = 2024$
$d = 0.3$	$t = 2022$
$d = 0.5$	$t = 2022$
$d = 0.7$	$t = 2022$
$d = 1.0$	$t = 2022$
$d = 2.0$	$t = 2022$
$d = 3.0$	$t = 2022$

DRR = disaster risk reduction, GDP = gross domestic product, SFDRR = Sendai Framework for DRR.
Source: From the case study results of the model in this paper (see Appendix for detailed input data).

5. Conclusion

5.1. General Conclusions

In this research, a case study on Indonesia was conducted, in which a dynamic stochastic macroeconomic model was used as a means of quantitatively analysing the long-term effects on economic growth that are brought about by DRR investments as well as large-scale disasters that occur in developing countries, including those of the ASEAN Community. In presenting the results of this research, several DRR investment policies that are concerned with the protection of economic and social assets were also proposed. First, this study found that economic growth in Indonesia was being affected by catastrophic disasters and investment in DRR was required to reduce disaster risks, For instance, in 2004, the year in which the Indian Ocean earthquake and tsunami occurred in Indonesia, it was estimated that the economic growth in the case of the current 0.1%-DRR policy was 0.19% lower than that outlined in the optimal 0.5%-DRR policy. Second, this research revealed that in Indonesia, although greater economic growth is expected when additional DRR investments are made, an excessive DRR investment may contrarily lead to a slowdown in economic growth. Hence, maintaining an optimal level of DRR investment is essential. Through this case study, the optimal level of DRR investment in Indonesia was estimated to be about 0.5% of the GDP, and it was demonstrated that whether or not this level of DRR investment is provided makes a big difference in long-term economic growth. Since it is visually difficult to understand the effects of DRR until a large-scale disaster has occurred, and as the effects of investments in other projects within which said effects are visible over a short term basis are prone to be prioritised, quantitatively showing the optimal percentage of DRR investments would be effective as a normative value toward securing DRR budgets. Third, it was found that in Indonesia, the net profit for DRR investment is obtained at a relatively early stage, so long as the DRR investment is not excessive. The net profit has a tendency to increase year by year, and thus this demonstrated that DRR investments are reasonable in the long term. Furthermore, the DRR investment level with the highest economic efficiency was estimated to be about 0.3% of the GDP, and it was also estimated that this DRR investment level would prevent a direct economic loss of US$10.4 on average for every US$1 of DRR investment in 2030. Fourth, it was confirmed that the ex-ante risk reduction effect will definitely be generated even when no disaster damage is caused over a long period of time. This therefore indicates that DRR investments are by no means redundant. It was also estimated that for Indonesia, the DRR investment level that would maximise this effect would be around 0.5% of the GDP. Fifth, it was demonstrated that in Indonesia, providing continuous DRR investments is important in achieving Global Target 3 in the Sendai Framework for Disaster Risk Reduction 2015–2030. Furthermore, it would also be desirable to maintain a DRR investment level that is higher than the current level.

5.2. Specific Recommendations

There are several recommendations for further research towards expanding the range of proposals for future DRR investment policies and improving the accuracy of these proposals. First, in the future, after accumulating accurate data on the disaster damage incurred in Indonesia where this case study was conducted, it would be necessary to update and improve the disaster damage rates and the parameters of the disaster damage mitigation function, as well as to improve the accuracy of numerical simulations by raising the reproducibility of current conditions. Hence, the most important aspect is the continuous collection and accumulation of data on disaster damage. Second, with regard to the dynamic optimisation issue, after endogenously deriving the optimal DRR investment level for each year by defining the DRR investment level that is currently treated as a policy variable as a control variable, it would also be necessary to determine the formation level of each type of capital, as well as the DRR investment level that corresponds to economic growth. Third, by classifying DRR investment policies into hard and soft policies, it would be necessary to propose disaster prevention policies with the best mix of these two types of policies. Fourth, this research deals with flood damage only. However, by dealing with multiple disaster types simultaneously, including geological disasters such as earthquakes or meteorological disasters such as storms, it would be necessary to create an improvement in the reproducibility of current conditions as well as the accuracy of future predictions. Fifth, it is necessary to expand the model into one that is capable of evaluating social disparities by dividing income classes and showing social indicators such as the Gini coefficient. For example, by expanding the model to a multi-income level model, it will be possible to conduct an analysis that focuses on people of the poorest social class as well as the impact of DRR investments on the social disparities across the country. Finally, by expanding the model to a multiregional and multisectoral model, it will be possible to analyse the regional impact of natural disasters and DRR investments in detail, in a way that may be difficult to see if analysed at the national level.

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Appendix: List of data used

Table A1: Socio-economic Data

Symbol	Definition	Value	Note
ρ	Time preference rate	0.02	By assumption
$\bar{c}$	Minimum subsistence level of consumption	100 (US$)	By assumption
θ_j	Degree of relative risk aversion	$\{\theta_c, \theta_z\} = \{2.0, 2.1\}$	By assumption
$\delta_{\tilde{x}}$	Depreciation rate of each type of stock	$\{\delta_z, \delta_k, \delta_g\} = \{0.04, 0.02, 0.04\}$	By assumption
α_i	Share parameter of production factors	$\{\alpha_h, \alpha_k\} = \{0.46, 0.54\}$	By calibration (Yusuf, 2006)
γ_j	Weight on utility of consumption and household assets	$\{\gamma_c, \gamma_z\} = \{0.29, 0.71\}$	By calibration (Yusuf, 2006; World Bank; Federal Reserve Bank of St. Louis)
ν_x	Effect parameter of disaster damage mitigation	$\{\nu_\omega, \nu_\phi, \nu_\psi, \nu_\sigma\} = \{1.22, 0.98, 0.98, 0.98\}$	By assumption and estimation (Cabinet Office, Government of Japan; Ministry of Land, Infrastructure, Transport and Tourism, Government of Japan; World Bank)
N_0	Total population in initial period	220.5 (million people)	From statistical data (World Bank)
n	Population growth rate	1.3 (%)	From statistical data (average of 2003-2016; World Bank)
B_0	Total factor productivity (TFP) in initial period	8.27	By calibration (Yusuf, 2006; World Bank; Federal Reserve Bank of St. Louis)
β	TFP growth rate	3.8 (%)	By assumption
$a(0)$	Total assets in initial period	38,471 (US$)	By estimation (Yusuf, 2006; World Bank; Federal Reserve Bank of St. Louis)
$g(0)$	DRR capital in initial period	24.2 (US$)	By assumption and estimation (World Bank; Darwanto, 2012)
$d(0)$	Present DRR investment rate accounted for GDP	0.1 (%)	From previous research (average of 2006-2012; Darwanto, 2012)

Table A2: Disaster-related Data

Symbol	Definition	Value	Note
μ^l	Disaster occurrence probability	$\{\mu^1, \ldots, \mu^5\} = \{0.16, 0.34, 0.34, 0.14, 0.02\}$	By assumption and estimation (Data provided by BNPB)
ω_0^l	Initial labour damage rate	$\{\omega_0^1, \ldots, \omega_0^5\} = \{0.36, 0.77, 1.47, 1.47, 1.47\} \times 10^{-2}$	By assumption and estimation (World Bank; data provided by BNPB)
ϕ_0^l	Initial household asset damage rate	$\{\phi_0^1, \ldots, \phi_0^5\} = \{0.02, 0.07, 0.16, 0.25, 0.39\} \times 10^{-2}$	By assumption and estimation (Federal Reserve Bank of St. Louis; data provided by BNPB)
ψ_0^l	Initial production capital damage rate	$\{\psi_0^1, \ldots, \psi_0^5\} = \{0.02, 0.07, 0.16, 0.25, 0.39\} \times 10^{-2}$	By assumption that $\psi_0^l = \phi_0^l$
σ_0^l	Initial DRR capital damage rate	$\{\sigma_0^1, \ldots, \sigma_0^5\} = \{0.02, 0.07, 0.16, 0.25, 0.39\} \times 10^{-2}$	By assumption that $\sigma_0^l = \phi_0^l$

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