Chapter 3

An Economic Analysis of Optimal Hybrid Infrastructure: A Theoretical Approach in a Hydro-Economic Model

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Abstract This chapter features the functions of green infrastructure and gray infrastructure in a hydro-economic model and integrates them into a hybrid infrastructure. We show that adding green infrastructure to an existing gray infrastructure generates a new benefit, which is referred to as absorption effects. Using the model, we investigate the optimal hybrid infrastructure by maximizing the social net benefits, in which disaster risk reduction is defined. We then discuss how green infrastructure can be used to augment existing gray infrastructure from the perspective of economic optimality. We derive some conditions to determine whether both or either of gray and green infrastructures should be introduced to implement disaster risk reduction.

Keywords Green infrastructure · Gray infrastructure · Hybrid infrastructure · Disaster risk reduction · Hydro-economic model

3.1 Introduction

The purpose of this chapter is to model the functions of green infrastructure (GNI) and gray infrastructure (GYI) to integrate them into a hybrid infrastructure (HBI) and to express it in a simple hydro-economic model for deriving optimal HBI.

Although ecosystem-based disaster risk reduction has been widely attracting attention, there are few theoretical analyses in economics; Barbier (2012) and Barbier and Enchelmeyer (2014) provide theoretical frameworks in the context of GNI to prevent storm surges in coastal areas, but they only focus on GNI.

Meanwhile, Onuma and Tsuge (2018) present a hydro-economic framework to compare GYI and GNI in terms of cost–benefit by considering the size of the population and formulating the features of their respective disaster prevention

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functions. In addition, disaster risk and disaster risk reduction are clearly defined in the above model. While this direction is suitable for discussing optimal disaster risk reduction, the model is based on a binary choice between GNI and GYI. In reality, even if a preventing flood infrastructure is called a GNI, it is often an HBI, i.e., a mixture of GNI and GYI. Examples include the “Slowing the Flow” project implemented in Pickering in the UK, which is known as a nature-based solution to flood management and uses one large storage bund to effectively reduce flooding (Nisbet et al., 2015). Therefore, providing a framework for the analysis of HBI is significant for the economic study of disaster prevention infrastructures, which are becoming increasingly important in the days of frequent natural disasters.

In this chapter, we formulate the features of HBI, which combine the features of GNI and GYI, and construct a hydro-economic model expressing HBI. We then show that adding GNI to an existing GYI to form an HBI generates a new benefit, which is referred to as absorption effects. We then discuss how GNI can be used to augment existing GYI from the perspective of economic optimality.

3.2 Green, Gray, and Hybrid Infrastructures

Let us consider a hazard or rainfall that leads to a flooding river. In this chapter, we use “hazard” and “rainfall” exchangeably and denote it by H . Residents directly face H if there is no preventing infrastructure, whereas H is mitigated if we introduce GNI and/or GYI.

3.2.1 Green Infrastructure

We consider a GNI, which is often exemplified by forests located in the upstream of the river. GNI has the ability to save water. In the case of forests, some of the water that flows in does not flow out because it penetrates the ground or stays on the leaves, while the capacity of water saving is limited.

Let X_f denote the direct outflow from the GNI or the forest. X_f is the level of H net of the level of flow absorbed by the GNI, which is denoted by A . Therefore, $X_f = H - A$. The level of rainfall at which the capacity of absorption is used up is expressed by $\hat{H}$. $\hat{H}$ is supposed to increase with the scale of the forest, K_f , so we define $\hat{H}$ as

$$\hat{H} = \hat{H}(K_f) \quad (3.1)$$

with $\hat{H}'(K_f) > 0$. The level of absorption depends on K_f and H . A larger forest flows out smaller X_f , that is, higher A . Thus, we write A as $A(H, K_f)$. We assume that A increases with H up to $\hat{H}$, whereas A is constant with H beyond $\hat{H}$. On the

Fig. 3.1 Outflow X_f and absorption $A(H, K_f)$ of GNI

contrary, X_f also increases with H . That is, for $H < \hat{H}$, $0 < A'_H (\equiv \partial A / \partial H) < 1$, and $A''_H (\equiv \partial^2 A / \partial H^2) < 0$. Moreover, $A'_H = 0$ for $H \geq \hat{H}$ and $A'_{K_f} > 0$.

The maximum absorption of the forest, $\hat{A}$, is defined as

$$\hat{A} = A(\hat{H}, K_f) \equiv \hat{A}(K_f) \quad (3.2)$$

By definition, we have $\hat{A}' > 0$ and $A(H, K_f) < \hat{A}(K_f)$ for $H < \hat{H}$. In summary, the resulting outflow from GNI, X_f , is determined as

$$X_f = \begin{cases} H - A(H, K_f) & \text{for } H < \hat{H} \\ H - \hat{A}(K_f) & \text{for } H \geq \hat{H} \end{cases} \quad (3.3)$$

X_f is described in Fig. 3.1.

3.2.2 Gray Infrastructure

Let K_c represent the GYI. Let H_c be the hazard or flow arriving to GYI. Following Onuma and Tsuge (2018), GYI protects the flow completely up to a threshold $\hat{H}_c$, but it does not protect beyond $\hat{H}_c$. We call $\hat{H}_c$ *threshold hazard*, which increases with K_c ; that is, the threshold hazard increases as the scale of the GYI increases. We assume that the threshold hazard is proportional to the scale of K_c :

$$\hat{H}_c = \theta K_c \quad (3.4)$$

Therefore, the resulting hazard that the residents face, X_c , is expressed as

$$X_c = \begin{cases} 0 & (H_c \leq \hat{H}_c) \\ H_c & (H_c > \hat{H}_c) \end{cases} \quad (3.5)$$

As noted by Onuma and Tsuge (2018), the most striking difference between GNI and GYI is their hazard prevention rates: in GYI, the rate is 1 up to the threshold but zero beyond that, while the rate never becomes 1 but is always positive in the case of GNI.

3.2.3 Hybrid Infrastructure

In our model, an HBI is defined as a mixture of GNI and GYI. A GNI is located upstream of the river, while a GYI is built downstream to protect nearby residents. Therefore, X_f in (3.3) flows to the GYI. That is,

$$H_c = X_f = H - A(H, K_f) < H \quad (3.6)$$

In this way, GNI mitigates the hazards coming to GYI. X_h denotes the hazard resulting from the HBI. GYI itself protects against the hazard completely up to a threshold of $\hat{H}_c$, but it fails beyond $\hat{H}_c$; that is,

$$X_h = \begin{cases} 0 & (X_f \leq \hat{H}_c) \\ X_f & (X_f > \hat{H}_c) \end{cases} \quad (3.7)$$

This is a function of the HBI (K_c, K_f) . Under the HBI, we derive the level of hazard H^* such that

$$X_f^* \equiv H^* - A(H^*, K_f) = \hat{H}_c \Rightarrow H^* = \hat{H}_c + A(H^*, K_f) \quad (3.8)$$

That is, H^* is the level of rainfall in a forest where flow to GYI attains the threshold hazard $\hat{H}_c$. This shows that the threshold hazard increases from $\hat{H}_c$ under $(K_c, 0)$ to $A(H^*, K_f) + \hat{H}_c$ under (K_c, K_f) . Let H^* be $\hat{H}_c + \omega$, which is the new threshold under HBI. Then, it holds that $\hat{H}_c + \omega = \hat{H}_c + A(\hat{H}_c + \omega, K_f)$, so

$$\omega = A(\hat{H}_c + \omega, K_f) \quad (3.9)$$

ω is an important variable when considering the HBI, in that the threshold hazard of GYI increases as a result of setting the GNI. We may call ω a *substantial increment in threshold hazard*. In the following lemma, we prove that ω is determined uniquely, given (K_c, K_f) .

Lemma 1 For any $\hat{H}_c > 0$, ω satisfying (3.9) exists uniquely.

Proof From the definition of A , it holds that $0 < A(\hat{H}_c + \omega, K_f) \leq \hat{A}(K_f)$. This means that there always exists a ω belonging to $(0, \hat{H})$ that satisfies (3.9). Next, suppose that there exist ω_1 and ω_2 with $\omega_1 > \omega_2$ that satisfy (3.9) for some $\hat{H}_c > 0$. However, this implies

$$\omega_1 - \omega_2 = A(\hat{H}_c + \omega_1, K_f) - A(\hat{H}_c + \omega_2, K_f) \quad (3.10)$$

However, this is not feasible because we assume that $A'_H < 1$. Thus, ω that satisfies (3.9) must be unique. $\square$

The next lemma shows that ω depends on GYI as well as GNI when GYI is not large enough.

Lemma 2 For $\hat{H}_c > 0$ and ω satisfying (3.9),

$$\frac{d\omega}{d\hat{H}_c} = \frac{A'_H}{1 - A'_H} \geq 0$$

where equality holds only if $A(H, K_f) = \hat{A}(K_f)$ or $\hat{H}_c + \omega \geq \hat{H}$.

Proof Differentiating (3.9) leads to

$$d\omega = A'_H(d\hat{H}_c + d\omega) \quad (3.11)$$

From here, we obtain $\frac{d\omega}{d\hat{H}_c} = \frac{A'_H}{1 - A'_H}$, where $A'_H = 0$ if $\hat{H}_c + \omega \geq \hat{H}$. $\square$

Then, we get the following result, which shows the magnitude of the substantial increment in the threshold hazard.

Proposition 1 The HBI increases the threshold $\hat{H}_c$ by ω where (i) $\omega = \hat{A}(K_f)$ if $\hat{H}_c \geq \hat{H} - \hat{A}(K_f)$. (ii) $\omega < \hat{A}(K_f)$ if $\hat{H}_c < \hat{H} - \hat{A}(K_f)$.

Proof For $\hat{H}_c = \hat{H} - \hat{A}(K_f)$,

$$A(\hat{H}_c + \omega, K_f) = A(\hat{H} - \hat{A}(K_f) + \omega, K_f) \quad (3.12)$$

It is obvious that if $\omega = \hat{A}(K_f)$, (3.9) is satisfied as

$$\omega = A(\hat{H}_c + \omega, K_f) = A(\hat{H}, K_f) = \hat{A}(K_f) \quad (3.13)$$

Then, from Lemma 1, $\omega = \hat{A}(K_f)$ is the solution of (3.9). Moreover, from Lemma 2, $A'_H = 0$ at $\hat{H}_c$, so $\omega = \hat{A}(K_f)$ is also the solution for $\hat{H}_c > \hat{H} - \hat{A}(K_f)$. Furthermore, for $\hat{H}_c < \hat{H} - \hat{A}(K_f)$, Lemma 2 says $\omega < \hat{A}(K_f)$. $\square$

Fig. 3.2 Prevention of hazard by HBI and GYI

In summary, by introducing (K_c, K_f) , the resulting hazard H_h is

$$H_h = \begin{cases} 0 & (H \leq \hat{H}_c + \omega) \\ H - \omega & (H > \hat{H}_c + \omega) \end{cases} \quad (3.14)$$

Equation (3.14) is depicted in Fig. 3.2, where $\hat{H}_c \geq \hat{H} - \hat{A}(K_f)$ so that $\omega = \hat{A}(K_f)$. In the figure, the benefits of HBI can be graphically compared with GYI. HBI, in which GNI is added to the existing GYI, provides two benefits. First, even though the hazard is higher than $\hat{H}_c + \omega$, which means that the hazard cannot be prevented, it is always mitigated. It is worth noting that this benefit cannot be obtained by setting GYI solely; any hazard beyond the new threshold hazard is mitigated in HBI, due to the function of GNI.

Second, the threshold $\hat{H}_c$ of GYI increases by ω , despite the fact that GYI is kept the same as before. It might be interesting that the magnitude of ω sometimes depends on K_c as well as K_f , as demonstrated by Lemma 2. This occurs when K_c is not sufficiently large enough so that $\hat{H}_c < \hat{H} - \hat{A}(K_f)$ by proposition 1. This property might be important when we consider the replacement of a part of the preventing function of GYI with GNI. In the replacement, suppose that we keep the threshold hazard as before. It might be intuitive that ω depends only on K_f and is determined independently of K_c . However, if K_c is not large enough, if there is a decrease in K_c , it will reduce ω . Hence, without careful planning, such replacement could result in the reduction of the threshold hazard.

These features are depicted in Fig. 3.3, which expresses $A(H, K_f)$ as a green line. Suppose that the initial threshold hazard is $\hat{H}_c^0$, in which case the substantial increment in the threshold hazard ω , created by K_f , is ω_0 . The figure shows that if

Fig. 3.3 Change of ω as a result of reducing $\hat{H}_c$

$\hat{H}_c^0$ is reduced to $\hat{H}_c^1$, ω_0 decreases to ω' . On the contrary, if we suppose that the initial threshold hazard is sufficiently large, $\hat{H}_c^2$, where $\omega = \omega_2$. In this case, even if $\hat{H}_c^2$ is reduced to $\hat{H}_c^3$, which changes ω_2 to ω'' , the level of ω is equivalent.

3.2.4 Ratios of Prevented Hazard by GNI and GYI

As shown by (3.14), the HBI completely prevents any hazard H below $\hat{H}_c + \omega$ and partly H beyond it. Now that we have a mixture of two preventing hazard infrastructures, GNI and GYI, in HBI, seek each ratio of hazard that is prevented in each infrastructure. Given (K_c, K_f) , we define $r_f = (H - X_f)/H = A(H, K_f)/H$ and $r_c = (X_f - X_h)/H$, which formally shows the ratio of hazard prevention. Thus, in terms of (3.14), both r_f and r_c are positive with $r_f + r_c = 1$ for $H(< \hat{H}_c + \omega)$, whereas $r_f > 0$, but $r_c = 0$ for $H(> \hat{H}_c + \omega)$, where $r_f + r_c < 1$.

Note that $r_f(H)$ decreases with H because $A''_H > 0$ for $H < \hat{H}$ and $A'_H = 0$ for $H \geq \hat{H}$. Note also that

$$r_f(0) = \lim_{H \downarrow 0} \frac{A(H, K_f)}{H} = A'_H(0, K_f) \quad (3.15)$$

by l'Hôpital's rule. Thus, we can describe the behavior of r_f and r_c as follows.

Proposition 2 *In HBI expressed by (3.14), the ratio of prevention by GNI, $r_f = A(H, K_f)/H$, decreases with H from $r_f(0) = A'_H(0, K_f)$. Meanwhile, the ratio of GYI, $r_c = (X_h - X_f)/H$, is equal to $1 - r_f$ for $H(< \hat{H}_c + \omega)$ and to zero for $H(\geq \hat{H}_c + \omega)$.*

Fig. 3.4 r_c and r_f

Figure 3.4 depicts r_c and r_f .¹ GNI reduces the flow considerably when the rainfall is small.

3.3 Optimal Hybrid Infrastructure

In this section, we incorporate the function of HBI into a simple economic model, that is, a hydro-economic model, and analyze some properties of the optimal HBI. We define disaster risk reduction (DRR) in this model. Denoting the considerable maximum hazard with H^m , let $f(H) : [0, H^m] \rightarrow [0, 1]$ be the function expressing the probability that a hazard H occurs, with $\int_0^{H^m} f(H)dH = 1$. The hazard risk is defined as $HR = \int_0^{H^m} f(H)HdH$.

In contrast, $D(H)$ shows the disaster caused by hazard H , where $D(0) = 0$, $D' > 0$, $D'' > 0$. That is, the marginal disaster of hazard is positive and

¹ Although $A''_H < 0$, the signs of r''_f and r''_c are ambiguous. Figure 3.4 shows that A''_H is small enough ($|A''_H|$ is large enough), so that $r''_f < 0$ and $r''_c > 0$ for $H(< \hat{H})$. It is possible that the opposite case occurs, depending on the value of A''_H . However, $r''_f > 0$ for $H(\geq \hat{H})$.

increases with H . Disaster risk (DR) without preventing infrastructure, that is, $(K_c, K_f) = (0, 0)$, is defined as

$$DR(0, 0) = n \int_0^{H^m} f(H) D(H) dH \quad (3.16)$$

where n is the population exposed to hazard H . On the contrary, DR under GYI, that is, $(K_c, K_f) = (K_c, 0)$ from (3.5) with its threshold hazard, $\hat{H}_c$, is expressed as

$$DR(K_c, 0) = n \int_{\hat{H}_c}^{H^m} f(H) D(H) dH \quad (3.17)$$

Disaster risk reduction by installing GYI at the initial state without preventing infrastructure, DRR from $(0, 0)$ to $(K_c, 0)$ is, therefore, defined as

$$DRR((K_c, 0)|(0, 0)) = DR(0, 0) - DR(K_c, 0) = n \int_0^{\hat{H}_c} f(H) D(H) dH \quad (3.18)$$

$DRR((K_c, 0)|(0, 0))$ is considered to be the benefit of setting GYI to the site without preventing infrastructures.

Now, let us suppose that the government strengthens an existing GYI to increase the threshold hazard from $\hat{H}_c$ by ΔH to $\hat{H}_c^* (= \hat{H}_c + \Delta H)$ by investing I_c into GYI and/or by introducing GNI. That is, we introduce (I_c, K_f) to satisfy

$$\theta I_c + \omega = \Delta H \quad (3.19)$$

Here, we assume that $\hat{H}_c$ is large enough in view of proposition 1 to satisfy $\omega = \hat{A}(K_f)$. This increment can be implemented only with $I_c = \theta^{-1} \Delta H$, where GYI increases to $K_c + \theta^{-1} \Delta H$; or only with $K_f = \hat{A}^{-1}(\Delta H)$; or with a mixture of I_c and K_f satisfying (3.19).

Disaster risk under this improvement is

$$DR(K_c + I_c, K_f) = n \int_{\hat{H}_c^*}^{H^m} f(H) D(H - \hat{A}(K_f)) dH \quad (3.20)$$

Thus, DRR gained by this improvement is defined as

$$\begin{aligned} DRR((K_c + I_c, K_f)|(K_c, 0)) &= n \int_{\hat{H}_c}^{\hat{H}_c^*} f(H) D(H) dH \\ &\quad + n \int_{\hat{H}_c^*}^{H^m} f(H) (D(H) - D(H - \hat{A}(K_f))) dH \end{aligned} \quad (3.21)$$

The first term is the benefit from enhancing the threshold hazard, which we call the *threshold effect*. The second term, however, is the benefit from absorption by GNI, which we call the *absorption effect*.

Let us define the costs of implementing $\hat{H}_c + \Delta H$. We denote the cost of expanding GYI as $C_c(I_c)$, assuming $C'_c > 0$ and $C''_c \geq 0$. On the contrary, the cost of GNI is expressed as $\mu C_f(K_f)$, where $\mu(> 0)$ reflects the opportunity costs of setting GNI or the prices of land acquired for setting GNI because GNI requires a wider range of geographic spaces. We assume $C'_f > 0$ and $C''_f > 0$.

Meanwhile, environmental benefits and costs are included as $E_f = \alpha_f K_f$ ($\alpha_f > 0$) for GNI and $E_c = -\alpha_c K_c$ ($\alpha_c > 0$) for GYI, where $\alpha_f > 0$ and $\alpha_c > 0$. Then, social net benefit, W , is expressed by

$$W = DRR((K_c + I_c, K_f)|(K_c, 0)) - C_c(I_c) - \mu C_f(K_f) + \alpha_f K_f - \alpha_c I_c \quad (3.22)$$

The optimal HBI is defined as maximizing (3.22) with (I_c, K_f) subject to (3.19). Assume that

$$\hat{A}(K_f) = \gamma K_f, \gamma > 0 \quad (3.23)$$

The optimum must satisfy if it is interior (both I_c and K_f are positive)

$$n \int_{\hat{H}_c^*}^{H^m} f(H) D'(H - \gamma K_f) \gamma dH = (\mu C'_f - \alpha_f) - \frac{\gamma}{\theta} (C'_c + \alpha_c). \quad (3.24)$$

γ/θ shows how much I_c is replaced by one unit, say, one hectare increase in K_f . Here, the left-hand side is the marginal absorption effect of this (marginal) replacement, while the right-hand side is the marginal net cost of replacement, including environmental benefits and costs. Equation (3.24) states that the marginal absorption effect must be equal to the net cost of replacement.

To make the argument clearer, we specify the function C_c as $C_c(I_c) = q I_c$ ($q > 0$), where q denotes the unit cost of investing in GYI. Moreover, the l.h.s. of (3.24) is denoted by $V(K_f)$ for convenience, where it holds that $V' < 0$. Let us denote the maximum feasible GNI as $\bar{K}_f \equiv \Delta H/\gamma$. Note that $V(0) > V(K_f) > V(\bar{K}_f)$ for $K_f \in (0, \bar{K}_f)$. Then, $K_f = 0$ becomes optimal if and only if

$$V(0) + \alpha_f + \frac{\gamma}{\theta} (q + \alpha_c) \leq \mu C'_f(0) \quad (3.25)$$

where $I_c = \Delta H/\theta$. The l.h.s. of (3.25) includes the marginal benefit from launching GNI, marginal absorption benefit, and marginal environmental benefit, added by the saved marginal costs of GYI. Roughly, this occurs when $\mu C'_f(0)$ is sufficiently high.

Developing even the first hectare of GNI is very costly, relative to the unit investment cost q . However, $I_c = 0$ is optimal if and only if

$$V(\bar{K}_f) + \alpha_f + \frac{\gamma}{\theta}(q + \alpha_c) \geq \mu C'_f(\bar{K}_f) \quad (3.26)$$

This condition is satisfied when $\mu C'_f(\bar{K}_f)$ is still low enough, even though the targeted increase in threshold hazard is achieved only by GNI. We state these properties in the following proposition.

Proposition 3 *To enhance the threshold hazard from $\hat{H}_c$ by ΔH , no use of GNI (i.e., $K_f = 0$) is optimal if $\mu C'_f(0)$ is sufficiently high to satisfy (3.25). On the contrary, zero investment in GYI, that is, $I_c = 0$, is optimal if $\mu C'_f(\bar{K}_f)$ is sufficiently low to satisfy (3.26). Otherwise, it holds that $(I_c, K_f) \gg (0, 0)$, where (3.24) is satisfied.*

Let us suppose that the optimum is interior; that is, (3.24) is satisfied at the optimum. Now, we assume that μ depends on n , which can be justified by the fact that the opportunity cost of setting GNI increases with the size of the population. Thus, $\mu = \mu(n)$, with $\mu' > 0$. Let ϵ_μ express the population elasticity of opportunity cost, that is, $\epsilon_\mu = n\mu'/\mu$, which expresses how much the percentage of opportunity cost increases when population increases by 1%. We observe the sign of dK_f/dn to see how the use of GNI changes with population.

Proposition 4 *Suppose that both I_c and K_f are positive under the optimum HBI. Then, it holds*

$$\frac{dK_f}{dn} \leq 0 \Leftrightarrow \epsilon_\mu \geq 1 - \frac{\alpha_f + \gamma\theta^{-1}(q + \alpha_c)}{\mu C'_f}$$

Proof Differentiating K_f with n under (3.24) leads to

$$\begin{aligned} \frac{dK_f}{dn} &= \frac{\int_{\hat{H}_c^*}^{H^m} f(H)D'(H - \gamma K_f)\gamma dH - \mu' C'_f}{\mu C''_f + n \int_{\hat{H}_c^*}^{H^m} f(H)D''\gamma^2 dH} \\ &= \frac{\mu C'_f(1 - \epsilon_\mu) - (\alpha_f + \gamma\theta^{-1}(q + \alpha_c))}{n(\mu C''_f + n \int_{\hat{H}_c^*}^{H^m} f(H)D''\gamma^2 dH)} \end{aligned} \quad (3.27)$$

using $\int_{\hat{H}_c^*}^{H^m} f(H)D'(H - \gamma K_f)\gamma dH = ((\mu C'_f - \alpha_f) - \frac{\gamma}{\theta}(C'_c + \alpha_c))/n$ from (3.24). Then, since the denominator is positive, the claim is straightforward from the numerator. $\square$

It should be noted that $0 < (\alpha_f + \gamma\theta^{-1}(q + \alpha_c))/\mu C'_f < 1$ holds because the r.h.s. of (3.24) must be positive. Therefore, a paradoxical case $dK_f/dn > 0$ occurs if ϵ_μ is sufficiently small, as in the claim. In other cases, the share of GNI use decreases when implementing ΔH as population increases.

3.4 Concluding Remarks

This chapter formalizes HBI and incorporates it into economics. Based on the model, we discuss the optimal mixture of GNI and GYI, that is, the optimal HBI.

To augment the disaster prevention function of the existing GYI, we show the nature of the optimal HBI. In particular, the logic for not using GNI at all is justified only when the marginal cost, including the opportunity cost when deployment is still zero, is sufficiently high, i.e., (3.25) holds. As the opportunity costs are expected to be lower for smaller populations, it is likely that the augmentation of disaster risk reduction infrastructure without the use of GNI would be inefficient, especially in sparsely populated areas.

In this chapter, GNI is assumed to be located upstream of GYI, but it is also possible that GYI is the first to receive the hazard and GNI is located behind it, as in the case of coastal seawalls. An HBI with a different arrangement of GNI and GYI could also be characterized in the same way as described in this chapter. This attempt is left for future research.

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