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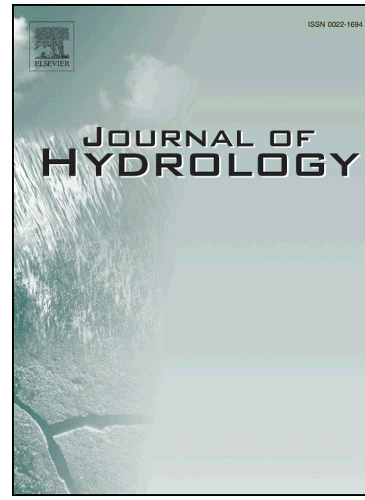

Research papers

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Flood Footprint Assessment: A New Approach for Flood-induced Indirect Economic Impact Measurement and Post-flood Recovery

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Abstract

Flooding in one location can impact the entire production chain of a regional economy. Neglecting the knock-on costs of this risks ignoring the economic benefits and beneficiaries of flood risk management interventions. However, economic consequence assessments in the existing studies are restricted to direct economic impact as there is not a generally accepted quantitative method to assess indirect economic impacts. This paper presents the full methodology for a novel flood footprint accounting framework -Flood Footprint Model - to assess the indirect economic impact of a flood event and simulate post-flood economic recovery situations throughout productions supply chains. Within the framework of Input-Output (IO) analysis, the model is built upon previous contributions, with: improvements regarding the optimization of available production imbalances; the requirements for recovering damaged capital; and an optimized rationing scheme, including basic demand and reconstruction requirements. The Flood Footprint Model will be applied into a hypothetical example with an extensive sensitivity analysis of the Flood Footprint Model performed, taking particular account of alternative labour and capital recovery paths.

Keywords:

flood footprint model; indirect economic impact accounting; input-output analysis; post-flood recovery simulation.

Highlights

- Flood Footprint Model enable to measure natural disaster's indirect economic impact
- Flood footprint is sensitivity to post-flood recovery scheme
- Labour and capital recovery path has a significant impact on the flood footprint

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1. INTRODUCTION

Floods are the most common of natural disasters that threaten the majority of regions at a global level with numerous and unacceptable consequences. Understanding the wide-ranging effects of a flood, and identifying cost-effective adaptation and mitigation strategies, is therefore a most important task for many countries, both developed and under-developed (CRED, 2016). In line with this, many studies are devoted to paying close attention to the social and economic impacts of natural hazards with attention often focused primarily on the direct loss of people and physical assets (Hallegatte et al., 2007; Okuyama and Santos, 2014). This has a drawback in that an increasing number of studies shows that direct economic losses usually are only a fraction of the total economic losses, and that the indirect economic impact may have a much larger influence (US National Research Council, 1999; Baade et al., 2007; Cunado and Ferreira, 2014; Scawthorn et al., 2006; Hallegatte and Przyluski, 2010; Okuyama and Santos, 2014; Kellenberg and Mobarak, 2011). Regarding the responsibility issue, there has been a shift in flood management from 'government' to 'governance' in recent years. When referring to flood risk management in particular there is an increasing preference for the notion of 'governance' that allocates responsibilities to multiple levels or actors rather than 'government' in which one single authority makes all the decisions (Mian, 2014). However, lack of analytical approach is able to quantify the industries' responsibilities in the aftermath of natural disasters.

In this study, the concept of a 'flood footprint' is applied to characterize the total economic impact of a flood event. The concept was proposed by Mendoza-Tinoco et al. (2017) to assist in quantifying the cumulative losses, both the direct and indirect ones, caused by a flood, until the economy has returned to its pre-disaster level. The direct flood footprint here refers to the short-term physical impacts on natural resources, people and tangible assets (World Bank, 2010), while the indirect footprint refers to the economic impact and/or loss resulting from flood-induced losses, delays, disruption of economic activities, and the costs of physical capital reconstruction (Hallegatte, 2008; Baghersad and Zobel, 2015).

In this paper we extend the method proposed by Mendoza-Tinoco et al. (2017), in particular, by considering **i)** the role of consumer and producer flexibility and adaptability and **ii)** the role of 'alternatives' in starting up and maintaining the recovery process. Therefore, this study is able to offer several post-flood economic recovery plans to policymakers by simulating various recovery conditions in the aftermath of a flood, such as alternative labour or capital recovery plans. As we shall show, the framework we propose can capture these new developments in a novel way. While certain factors are considered more rationally and accurately through mathematical and logical approaches, the main novelties of the proposed methodology are: **i)** recovery schemes for industrial and household capital loss, which are set as endogenous factors if merely considering industrial linkages; **ii)** estimation of degraded productive capacity constraints regarding labour and capital are provided; **iii)** an optimized rationing scheme including basic demand and reconstruction requirements are offered; and **iv)** various extensive sensitivity analyses based on alternative recovery plans.

2. SELECTED VIEWS OF INDIRECT LOSS ESTIMATION

Opinions vary considerably regarding the selection of quantitative methods for assessment of the economic impact of disaster, particularly as regards indirect economic impacts (Okuyama, 2014; Koks and Thissen, 2016). Direct economic loss due to a natural disaster is often estimated by government authorities or insurance companies through first-hand data surveys and interviews, or is calculated using disaster models based on the physical properties. Contrary to this, the methods of indirect impact analysis are still being refined.

Currently, we may distinguish four main approaches to estimating the indirect economic losses of a natural disaster. The first two methods are post-disaster economic surveying (Baade et al., 2007; Kroll et al., 1991; Molinari et al., 2014) and econometric modelling (Albala-Bertrand, 1993; Cavallo et al., 2013). Both methods are based on primary data sources. A weak point is that they may have trouble adequately capturing the many interrelationships in an economic system. The other two methods focus on the sectoral level and reflect the economic structure of a system by considering inter-industrial and inter-regional linkages. They are Input-Output (IO) models (Miller and Blair, 2009) and Computable General Equilibrium (CGE) models (Rose and Liao, 2005). Although the IO model can provide essential inter-industrial linkages, its technological ties are relatively rigid. Thus, this method is less appropriate under situations where market-based mechanisms play a significant role (Okuyama, 2014; Koks and Thissen, 2016). By contrast, the CGE models do consider the role of markets and allow for specific price adjustments (Carrera et al., 2015). However, CGE models may be overly optimistic regarding market flexibility (Rose, 1995; Berrittella et al., 2007; Carrera et al., 2015; Haddad and Teixeira, 2015; Kajitani and Tatano, 2017)

Of the above four approaches, IO analysis has a specific advantage in its relative simplicity and its ability to closely focus on the sectors' interdependencies (Hallegatte, 2008; In den Bäumen et al., 2015). Okuyama and Santos (2014) have reviewed IO models used for disaster impact assessment in recent years and noted that relative to the other three methods, IO analysis is more widely applied to indirect economic loss estimation, precisely because of its relative simplicity. For example, on the basis of IO theory, HAZUS-MH Model, an indirect damage estimation tool, was developed by the United States Federal Emergency Management Agency and the National Institute of Building Sciences, and later developed into a software programme (Scawthorn et al., 2006). The Indirect Economic Loss Model component of

HAZUS-MH Model uses the post-disaster surviving capacity in terms of surviving production as a starting point for recalculating inter-industry supplies and demands. However, as a tool, this model can only be fruitfully used for the United States since its default profile and basic input dataset was set based on the United States condition (Scawthorn et al., 2006a and 2006b; Remo et al., 2016).

Early research in the economic consequences of disasters assessment based on the IO model showed a general lack of attention for changes in productive capacity. Regarding this, Steenge and Bočkarjova (2007) proposed an 'imbalanced' recovery model to structure possible paths leading to reinstalling IO based forms of circular flow. Hallegatte (2008) built an Adaptive Regional Input-Output model (ARIO) to explore the influence of natural disasters and the ensuing recovery phase with consideration of production capacity changes resulting from capital loss-induced and consumption behaviour adaptation, as well as over-production possibilities and import substitutions. As a hybrid model, ARIO has two main contributions: one is that it introduced production capacity as a factor to link industrial productive capital damage and remaining production capacity; and the second is it incorporated adaptive behaviours, such as adapted local final demand and adapted export, to analyse the conditions of post-disaster economy. The model was then applied to estimate the losses by caused by Hurricane Katrina and to analyse the storm surge risks under a sea level rise scenario in Copenhagen (Hallegatte et al., 2011). Koks et al. (2015) employed both the imbalanced model and the ARIO model to simulate production loss and economic recovery in a post-disaster economy of the harbour area in Rotterdam (the Netherlands). The model attempted to capture the post-disaster economic dynamics with particular emphases on price adjustments and adaptations in final consumption, intermediate consumption and production. However, important imbalances were neglected, such as the links between capital availabilities and labour productivity.

Li et al. (2013) constructed a Basic Dynamic Inequalities model (BDI) to assess an imbalanced economic recovery in a post-disaster period, incorporating a series of dynamic inequalities. Mendoza-Tinoco et al. (2017) proposed a damage accounting framework that combines the advantages of previous IO-based disaster risk analysis models and introduced the flood footprint concept to estimate the total economic impacts of the 2007 summer floods in the region of Yorkshire and the Humber in the UK. Their methodologies followed the design of ARIO in terms of capturing post-disaster recovery, but with some improvements such as taking labour availability into consideration during the disaster aftermath. A major drawback is that the model treats imports as an exogenous variable by exogenously adding available imports to remaining production to fulfil both intermediate needs and final demand.

Overall, IO models are powerful tools to measure the economic consequences of external shocks on the economy. However, the rigidity embodied in traditional IO models does not allow the economy to flexibly respond to changes either in producing or consuming processes since production in the basic IO model is assumed as propagated among suppliers and consumers in fixed proportions. Therefore, 'adaptive models' are proposed to make it possible to consider less rigid ways of dealing with the remaining production possibilities and to be adaptive concerning the role of final demand in the post-disaster period.

The Flood Footprint Model developed in this paper seeks to quantify the flood-induced indirect flood footprint. The methodology for indirect flood footprint accounting offered here has specific novelties: **i)** the parameter of 'the basic demand' that mainly refers to human basic demand in the aftermath of disaster is firstly introduced into the model. Thus, it provides a more effective rationing scheme of post-flood available resources taking into consideration basic human requirements and industrial interdependencies; **ii)** the measurement of reconstruction demand during the recovery period becomes more independent when compared with the approaches proposed by Hallegatte (2008), Li et al. (2013) and Mendoza-

Tinoco et al. (2017), in which the capital reconstruction is significantly constrained by external investment or import. In this study, if there is no other specific recovery plan, reconstruction demand is set as an endogenous variable that merely relies on the economy by itself; and **iii)** it allows various types of sensitivity analysis to model parameters and other external influences, due to the flexibility and transparency of the model in which the recovery process can be clearly simulated.

3. METHODOLOGY OF THE FLOOD FOOTPRINT MODEL

The Flood Footprint Model that we shall discuss belongs to the class of ARIO models. It focuses on the post-disaster demand and supply imbalances, the distribution of the remaining capacity, and the role of producer and consumer adaptive behaviour. In a final section we shall draw attention to an issue that is becoming more important over time, i.e. the sensitivity of basic variables to delays in the recovery process.

We start with the basic Leontief IO model (Miller and Blair, 2009),

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{f} \qquad (1)$$

where $\mathbf{x}$ denotes industrial gross output and $\mathbf{f}$ final consumption demand which includes local household consumption, government expenditure, capital inventory and exports. $\mathbf{A}$ is the technical coefficients matrix, which is assumed to be unchanged throughout the period of analysis. The left-hand side of Eq.1 stands for total output of the economy, while the right-hand side stands for total demand.[1]

[1] Bold capital letters are used for matrices, as in **A**, lower-case bold letters for column vectors, as in **x**, transposition is denoted by an apostrophe as in $\mathbf{x}'$, while vector diagonalization is expressed as $\hat{\mathbf{x}}$. Scalars are represented by italic lower-case letters, as *x*.

Two assumptions are made: one is that foreign relations are abstracted in the pre-disaster situation; and the other is that imports, as external resources, are allowed during the post-flood recovery period. Before the flood occurs local production ($\mathbf{x^0}$) can satisfy intermediate demand ($\mathbf{Ax^0}$) and final consumption demand ($\mathbf{f^0}$) according to Eq.2.

$$\mathbf{x^0} = \mathbf{Ax^0} + \mathbf{f^0} \qquad (2)$$

$$\mathbf{f^0} = \mathbf{f^0_{hh}} + \mathbf{f^0_{gov}} + \mathbf{f^0_{cap}} + \mathbf{f^0_{exp}} \qquad (3)$$

where $\mathbf{f^0}$ is final demand (Eq.3) which includes household demand ($\mathbf{f^0_{hh}}$), government demand ($\mathbf{f^0_{gov}}$), capital inventory ($\mathbf{f^0_{cap}}$) and export ($\mathbf{f^0_{exp}}$).

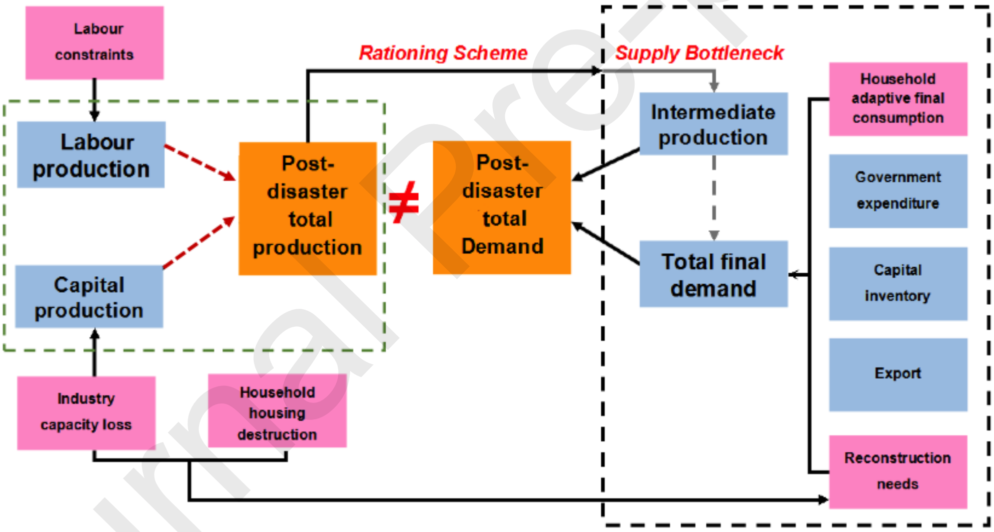

Figure 1. Post-disaster Imbalanced Economy and Recovery.

Many of the above balances will break up after the disaster (**Figure 1**). As input proportions are assumed to be fixed, capital damage and labour constraints will, in general, lead to a decrease in the capital and labour input. One reason for that is that capital and labour production capacity will tend to shrink disproportionally. Depending on the precise nature of the post-disaster imbalances, the proposed model will indicate which choices have to be made regarding priority. During the recovery process, five points in particular will be considered in the Flood Footprint Model: capital loss and damage, labour constraints, household consumption behaviour, supply bottlenecks and the presence of a rationing scheme. These points will be briefly discussed below.

3.1 Capital loss

Capital loss includes industrial capital loss and household capital loss. Industrial capital loss leads to reduction in production activities, while household capital loss does not impact production activities but needs to be repaired/replaced during recovery. Destroyed capital can be expected to result in decreased industrial production capacity. We can express this loss in capacity by introducing a new variable, $\mathbf{x}^{\mathbf{t}}_{\mathbf{cap}}$, which stands for the available capital capacity in period t. We have

$$\mathbf{x}^{\mathbf{t}}_{\mathbf{cap}} = (\mathbf{I} - \hat{\boldsymbol{\alpha}}^{t-1})\mathbf{x}^{\mathbf{0}} \ (t \geq 1) \qquad (4)$$

Here $\hat{\boldsymbol{\alpha}}^{t-1}$ is the diagonal matrix of industrial damage fractions caused in period t-1. Each diagonal element stands for the ratio of damaged industrial capital to industrial original capital stock; $\mathbf{x}^{\mathbf{0}}$ again is the pre-disaster output level. The recovery period starts at t=1. When t=1, α^0 is an exogenous factor which stands for the direct physical capital damage. For t>0, it can be endogenous or exogenous, depending on the assumptions made. For example, if there is no specific industrial capital recovery plan, α^t is an endogenous factor, related to the industrial reconstruction in the previous stages; if there are some specific industrial recovery plans, these may lead to exogenous α^t. Below, we shall focus on an endogenous α^t for appropriate t.

3.2 Labour constraints

For labour we employ a comparable structure. Actual production as limited by labour constraints ($\mathbf{x}^{\mathbf{t}}_{\mathbf{lab}}$) is given by Eq.5, where β^{t-1}.is the percentage of affected labour productivity at the end of period *t-1* where β^t is exogenous during the entire process.

$$\mathbf{x}_{\mathbf{lab}}^{\mathbf{t}} = \left(\mathbf{I} - \hat{\boldsymbol{\beta}}^{t-1}\right)\mathbf{x}^{\mathbf{0}} \quad (t \geq 1) \quad (5)$$

3.3 The Basic Demand

Household adaptive consumption behaviour during the flood aftermath is set exogenously as $\mathbf{f_{cd}}$, and can be changed in each stage. Size and composition of $\mathbf{f_{cd}^{t}}$ in period t thereby depends on policymakers, where we assume that consumers will accept their decisions. Regardless of the outcomes involving the size of $\mathbf{f_{cd}^{t}}$, allocation for production purposes in each period has priority. Furthermore, $\mathbf{f_{hh}}$ stands for household demand as given by the pre-disaster economic circumstances. If $\mathbf{f_{cd}}$ is assumed to be equal to $\mathbf{f_{hh}}$, $\mathbf{f_{cd}}$ can be given the value of $\mathbf{f_{hh}}$. If this is not the case, then $\mathbf{f_{cd}}$ and $\mathbf{f_{hh}}$ must be introduced separately.

3.4 Supply Bottleneck

Also introduced is a new component called recovered demand ($\mathbf{f_{rec}}$) (Eq.6), consisting of industrial capital recovery demand ($\mathbf{f_{ID}}$) and household recovery demand ($\mathbf{f_{HD}}$). This component is added to the final demand part (Eq.7). Total required production ($\mathbf{x_d}$) now is calculated given the new final demand ($\mathbf{f_d}$) (Eq.8).

$$\mathbf{f_{rec}} = \mathbf{f_{ID}} + \mathbf{f_{HD}} \quad (6)$$

$$\mathbf{f_d} = \mathbf{f_{hh}^0} + \mathbf{f_{gov}^0} + \mathbf{f_{cap}^0} + \mathbf{f_{exp}^0} + \mathbf{f_{rec}} \quad (7)$$

$$\mathbf{x_d} = \mathbf{A}\mathbf{x_d} + \mathbf{f_d} \quad (8)$$

Given the capital and labour limitations, and referring to Eqs.4 and 5, the actually available production ($\mathbf{x^t}$) is defined as the minimum of the production vectors as given by the capital and labour constraints (Eq.9), recalling that there is no workforce transfer among sectors (we did not consider that an electrician may switch to an IT job, but in reality, this transfer may occur). When the total required production exceeds the available production ($\mathbf{x_d} > \mathbf{x^1}$), it implies that the remaining production cannot support intermediate and final demand simultaneously, which then results in a supply bottleneck.

$$\mathbf{x^t} = \min(\mathbf{x^t_{cap}}, \mathbf{x^t_{lab}}) \quad (t \geq 1) \quad (9)$$ [2]

3.5 The Rationing Scheme

Less production in the flood aftermath will lead to a situation where import becomes the only way to meet the reconstruction needs. Import here is assumed to be closely related to the capacity of the transportation sector and the maximum capacity of import in the flooded area ($\mathbf{y^0_{imp}}$). For supporting the capital damage demand and basic demand, import is always provided during the whole disaster recovery period[3]. The amount of import at period t ($\mathbf{y^t_{imp}}$) is assumed to depend on the remaining capacity of the transportation sector (Eq.10), and, thus, is directly related to the damage fraction of transport sector (α^{t-1}_{tran}). α^{t-1}_{tran} means the ratio of damaged capital to the original capital stock of the transport sector, and is explained in Section 3.1. Taking imports into account, the total available production at each stage of the recovery period is ($\mathbf{x^t} + \mathbf{y^t_{imp}}$), where

$$\mathbf{y^t_{imp}} = (1 - \alpha^{t-1}_{tran})\mathbf{y^0_{imp}} \quad (t \geq 1) \quad (10)$$

If rationing is requested, decisions have to be made regarding the rationing scheme. The scheme we selected here is that available production should first be used for inter-industry demand, then go into the basic demand and final demand, where the complete recovery analysis will be based on two scenarios (scenario 1 and 2). Despite the choices that have been made, the scheme is of a very general nature, and can be adjusted according to different policies, such as forms of proportional rationing.

2 $\mathbf{x^t}$ selects for each element the smallest corresponding element of the vectors $\mathbf{x^t_{cap}}$ and $\mathbf{x^t_{lab}}$.
3 Here, it is assumed that the import stays exogenous through the whole process.

3.5.1 Scenario 1: recovery of intermediate linkages (Eq.11)

$$\mathbf{x^t} + \mathbf{y^t_{imp}} < \mathbf{Ax^0} + \mathbf{f^t_{cd}} \quad (t \geq 1) \qquad (11)$$

This scenario implies that all available production should be used to recover intermediate demand. As primary inputs ($\mathbf{Ax^0}$) must be used in fixed proportions in a standard IO model, a balance between capital and labour capacities will be restored first so that the production level can be raised back to the pre-disaster level. Taking the process of period t as an example, the details of the rationing scheme are shown below.

In Round t, production limited by industrial capital loss and labour constraint is quantified by Eqs.4 and 5. When considering the maximum capacity[4] of the economic system the available production ($\mathbf{x^t_{rem}}$) in Round t by considering the import become

$$\mathbf{x^t_{rem}} = \min\left(\mathbf{x^t} + \mathbf{y^t_{imp}}, \mathbf{x^0} + \mathbf{y^0_{imp}}\right) \quad (t \geq 1) \quad (12)$$

Import is treated as one part of domestic production, and a new balance is constructed (Eq.13). $\mathbf{A}$ still represents the domestic coefficients. The actual final demand ($\mathbf{f^t}$) under the new economic balance is obtained from Eq.14.

$$\mathbf{x^t_{rem}} = \mathbf{Ax^t_{rem}} + \mathbf{f^t} \quad (t \geq 1) \ (13)$$

$$\mathbf{f^t} = \mathbf{x^t_{rem}} - \mathbf{Ax^t_{rem}} \quad (t \geq 1) \quad (14)$$

Then the basic demand for minimal human needs ($\mathbf{f^t_{cd}}$) should be taken into account (Eq.15). If the final demand here is not able to satisfy the basic demand, i.e. if $\mathbf{f^t}$ is smaller than $\mathbf{f^t_{cd}}$, the allocation of the goods between the capital damage recovery demand and basic demand should be adjusted according to the different situations.

$$\mathbf{f^t_{rem}} = \mathbf{f^t} - \mathbf{f^t_{cd}} \quad (t \geq 1) \ (15)$$

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[4] In the original transections, it is assumes that import can be substituted by domestic goods or services, so when considering imports, the maximum capacity of the sector is the sum of domestic production and imports.

To repair the industrial capital damage, the residual final demand ($\mathbf{f^t_{rem}}$), is used first for industrial capital recovery ($\mathbf{f^t_{rec}}$; Eq.16) and then for other final demand ($\mathbf{f^t_{others}}$, Eq.17)[5]. The rest of recovery demand is the gap between total recovery demand ($\mathbf{f_{rec}}$) and the total recovered part before this round ($\sum_{\mathbf{t}=\mathbf{1}}^{\mathbf{t}-\mathbf{1}}\mathbf{f}^{k}_{\mathbf{rec}}, k \geq \boldsymbol{t} \geq \mathbf{1}$). $\mathbf{f^t_{others}}$ can include several users (similar to Eq.3), and the proportion of each part is determined by the recovery preferences.

$$\mathbf{f^t_{rec}} = \min\left(\mathbf{f_{rec}} - \sum_{\mathbf{t}=\mathbf{1}}^{\mathbf{t}-\mathbf{1}}\mathbf{f}^{k}_{\mathbf{rec}}, \mathbf{f^t_{rem}}\right) \quad (k \geq t \geq 1) \quad (16)$$

$$\mathbf{f^t_{others}} = \mathbf{f^t_{rem}} - \mathbf{f^t_{rec}} \quad (t \geq 1) \quad (17)$$

Capital damage fractions of each sector in the next round ($\boldsymbol{\alpha}^{\mathbf{t}}$), which considers the recovered industrial capital ($\mathbf{f_{rec}} - \sum_{\mathbf{t}=\mathbf{1}}^{\mathbf{t}}\mathbf{f}^{k}_{\mathbf{rec}}, k \geq t \geq 1$), are calculated by Eq.18, where $\mathbf{s^0}_{\mathbf{cap}}$ is the original industrial capital stock.

$$\boldsymbol{\alpha}^{\mathbf{t}} = \left(\widehat{\mathbf{s^0_{cap}}}\right)^{-1}\left(\mathbf{f_{rec}} - \sum_{\mathbf{t}=\mathbf{1}}^{\mathbf{t}}\mathbf{f}^{k}_{\mathbf{rec}}\right) \quad (k \geq t \geq 1) \quad (18)$$

Proceed until

$$\left(\mathbf{x^t} + \mathbf{y^t_{imp}} \geq \mathbf{Ax^0} + \mathbf{f^t_{cd}}\right)(t \geq 1) \quad (19)$$

then go to scenario 2.

3.5.2 Scenario 2: recovery of final demand (Eq.19)

$$\mathbf{x^t} + \mathbf{y^t_{imp}} \geq \mathbf{Ax^0} + \mathbf{f^t_{cd}} \quad (t \geq 1) \quad (19)$$

Intermediate industrial demand ($\mathbf{Ax^0}$) has already been satisfied and we can consider the allocation for other demand. Basic recovery demand should be treated as the priority. According to the conditions of the remaining production, scenarios 2.1 and 2.2 are analysed below (where $\mathbf{x^t}$ and $\mathbf{y^t}_{\mathbf{imp}}$ are estimated by Eqs.9 and 10).

5 Recall that in this case, we do not consider the competition among all final demand users.

3.5.2.1 Scenario 2.1

$$\mathbf{Ax^0} + \mathbf{f^t_{cd}} < x^t + \mathbf{y^t_{imp}} \le \mathbf{Ax^0} + \mathbf{f^t_{cd}} + \left(\mathbf{f_{rec}} - \sum_{\mathbf{t=1}}^{\mathbf{t-1}} \mathbf{f}^k_{\mathbf{rec}}\right) \quad (k \ge t \ge 1) \qquad (20)$$

This situation means that current production is sufficient for intermediate demand but cannot satisfy recovery demand and basic demand at the same time. Thus, other rest of production ($\mathbf{f^t_{new}}$) is used to support basic demand (Eq.21) and recovery demand (Eq.22), then for others (Eq.23). Meanwhile, the capital damage fraction of the next round is calculated with Eq.24.

$$\mathbf{f^t_{new}} = \min\left(\mathbf{x^t} + \mathbf{y^t_{imp}}, \mathbf{x^0} + \mathbf{y^0_{imp}}\right) - \mathbf{Ax^0} - \mathbf{f^t_{cd}} \quad (t \ge 1) \qquad (21)$$

$$\mathbf{f^t_{rec}} = \min\left(\mathbf{f_{rec}} - \sum_{\mathbf{t=1}}^{\mathbf{t-1}} \mathbf{f}^k_{\mathbf{rec}}, \mathbf{f^t_{new}}\right) \ (k \ge t \ge 1) \qquad (22)$$

$$\mathbf{f^t_{others}} = \mathbf{f^t_{new}} - \mathbf{f^t_{rec}} \ (t \ge 1) \qquad (23)$$

$$\boldsymbol{\alpha}^\mathbf{t} = \left(\widehat{\mathbf{s^0_{cap}}}\right)^{-1} \left(\mathbf{f_{rec}} - \sum_{\mathbf{t=1}}^{\mathbf{t}} \mathbf{f}^k_{\mathbf{rec}}\right). \ (k \ge t \ge 1) \qquad (24)$$

This situation holds until $\sum_{\mathbf{t=1}}^{\mathbf{t}} \mathbf{f}^k_{\mathbf{rec}} = \mathbf{f_{rec}} \ (k \ge t \ge 1)$ (25) and $\boldsymbol{\alpha}^\mathbf{t} = 0 \ (t \ge 1)$ (26). We then come to scenario 2.2.

3.5.2.2 Scenario 2.2

$$\mathbf{x^t} + \mathbf{y^t_{imp}} > \mathbf{Ax^0} + \mathbf{f^t_{cd}} + \mathbf{f_{rec}} (t \ge 1) \qquad (27)$$

When current production has met intermediate, recovery and basic demand, the rest of production is used to support other final demand. Equations for allocating available resources for each part of the final demand depend on different rationing schemes. Take a proportional rationing scheme as an example. At time period *t*, the recovery demand ($\mathbf{f^t_{rec}}$) and basic demand ($\mathbf{f^t_{cd}}$) are estimated separately as Eqs.28 and 29, and the allocation for other users ($\mathbf{f^t_{xx}}$) can be calculated through the example of household as Eq.30.

$$\mathbf{f^t_{rec}} = \left(\mathbf{x^t} + \mathbf{y^t_{imp}} - \mathbf{Ax^0}\right) \times \left(\left(\widehat{\mathbf{x_d}}\right)^{-1} \mathbf{f_{ID}}\right) \quad (t \ge 1) \qquad (28)$$

$$\mathbf{f}_{\mathbf{cd}}^{\mathbf{t}} = \left(\mathbf{x}^{\mathbf{t}} + \mathbf{y}_{\mathbf{imp}}^{\mathbf{t}} - \mathbf{Ax}^{\mathbf{0}}\right) \times \left(\left(\widehat{\mathbf{x}_{\mathbf{d}}}\right)^{-1}\mathbf{f}_{\mathbf{cd}}\right) \quad (t \geq 1) \qquad (29)$$

$$\mathbf{f}_{\mathbf{xx}}^{\mathbf{t}} = \left(\mathbf{x}^{\mathbf{t}} + \mathbf{y}_{\mathbf{imp}}^{\mathbf{t}} - \mathbf{Ax}^{\mathbf{0}}\right) \times \left(\left(\widehat{\mathbf{x}_{\mathbf{d}} - \mathbf{f}_{\mathbf{cd}}^{\mathbf{t}} - \sum_{\mathbf{t}=\mathbf{1}}^{\mathbf{t}} \mathbf{f}_{\mathbf{rec}}^{k\mathbf{t}}}\right)^{-1} \mathbf{f}_{\mathbf{xx}}^{\mathbf{0}}\right) \quad (k \geq t \geq 1) \qquad (30)$$

Then proceed until

$$\mathbf{f}_{\mathbf{rec}} + \mathbf{f}_{\mathbf{cd}}^{\mathbf{t}} + \mathbf{f}_{\mathbf{hh}}^{\mathbf{t}} + \mathbf{f}_{\mathbf{gov}}^{\mathbf{t}} + \mathbf{f}_{\mathbf{cap}}^{\mathbf{t}} + \mathbf{f}_{\mathbf{exp}}^{\mathbf{t}} = \mathbf{f}_{\mathbf{d}} \quad (t \geq 1)(31),$$

and

$$\mathbf{x}^{\mathbf{t}} = \mathbf{Ax}^{\mathbf{t}} + \mathbf{f}^{\mathbf{0}} \; (t \geq 1) \; (2).$$

3.6 Total flood footprint

When the economic imbalances return to the pre-disaster situation, all of the recovery period is complete. At this time, *t* denotes the time required to economic recovery, and the gap between the total production under pre-disaster level and the total required production of each round during the recovery process is the indirect economic loss of this disaster event (Eq.32); in other words, it is the amount of indirect impact ($x_{indirect}$; **Figure 2**). The total flood footprint (x_{total}) is the sum of the direct (x_{direct}) and indirect economic impacts (Eq.33). Many other results can be obtained from this model, such as how the destroyed capital is recovered step-by-step or how the labour affects the local economy.

$$x_{indirect} = sum\left(t\mathbf{x}^{\mathbf{0}} - \left(\sum_{\mathrm{t}=1}^{\mathrm{t}} \mathbf{x}^{k} + \sum_{\mathrm{t}=1}^{\mathrm{t}} \mathbf{y}_{\mathbf{imp}}^{k}\right)\right) \; (k \geq t \geq 1) \quad (32)$$

$$x_{total} = x_{direct} + x_{indirect} \qquad (33)$$

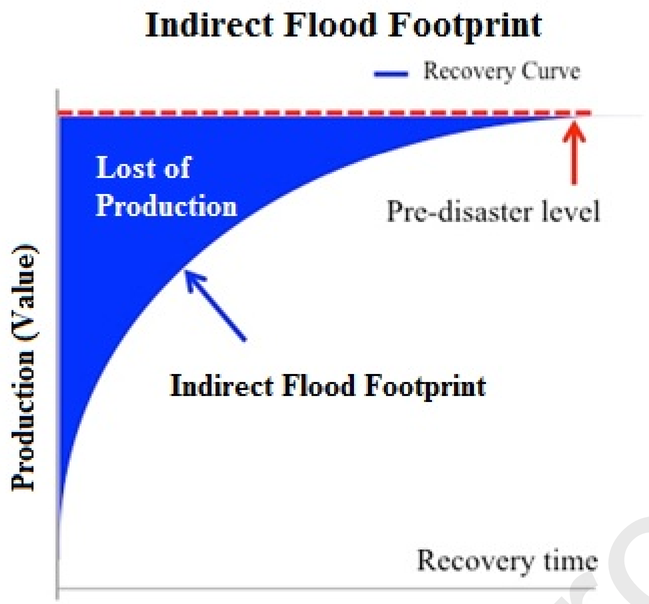


Figure 2. Indirect economic impact (for illustration purpose only).

4. HYPOTHETICAL NUMERICAL EXAMPLE

A hypothetical numerical example is proposed here for a better understanding of the Flood Footprint Model, supposing that the local economy has three sectors, Sector 1 (S1), Sector 2 (S2) and Sector 3 (S3); and S3 refers to transport sector. The basic IO data are shown in Table 1, the total output $\mathbf{x^0} = \begin{bmatrix} 1000 \\ 2000 \\ 1000 \end{bmatrix}$, the total final demand $\mathbf{f^0} = \begin{bmatrix} 300 \\ 1300 \\ 150 \end{bmatrix}$, and inter-linkages among these three sectors in terms of domestic coefficient $\mathbf{A} = \begin{bmatrix} 0.15 & 0.25 & 0.05 \\ 0.2 & 0.05 & 0.4 \\ 0.3 & 0.25 & 0.05 \end{bmatrix}$. The capital stock assumes as $\mathbf{s^0_{cap}} = \begin{bmatrix} 3500 \\ 5000 \\ 1500 \end{bmatrix}$ and basic demand of each sector is fixed at $\mathbf{f^t_{cd}} = \begin{bmatrix} 50 \\ 300 \\ 100 \end{bmatrix}$. The time unit of the recovery is a week. The damage of household i

s not considered in this example.

Table 1. Flows for hypothetical example (3×3)

To / From	S1	S2	S3	Final Demand (f^0)		Total Output (x)
				Basic demand (f_{cd})	Other demand (f_{others})	
S1	150	500	50	50	250	1000
S2	200	100	400	300	1000	2000
S3	300	500	50	100	50	1000
Import	25	100	200			
Other value-added	325	800	300			
Total Input	1000	2000	1000	350	1700	6150

Once a flood event occurs, the damage fraction of industrial capital in each sector is assumed to be $\boldsymbol{\alpha} = \begin{bmatrix} 0.4 \\ 0.5 \\ 0.3 \end{bmatrix}$, while the percentage of reduced labour time loss $\boldsymbol{\beta} = \begin{bmatrix} 0.5 \\ 0.4 \\ 0.2 \end{bmatrix}$. In addition, it is also assumed that the labour productivity of all three sectors are fully recovered during the first four weeks, and the recovery trends for S1 and S2 are non-linear lines, while S3 is linear line (Table 2). It should be noticed that due to a lack of practical data on post-flood labour productivity, data provided in Table 2 is only used for testing the flexibility of the Flood Footprint Model without any specific meanings in reality.

Table 2. Percentages of labour time loss of three sectors caused by the flood event.

	S1	S2	S3
Week 1	50%	40%	20%
Week 2	20%	20%	10%
Week 3	5%	5%	0%
Week 4	0%	0%	0%

Then, the recovery demand $\mathbf{f_{rec}}$ is $\begin{bmatrix}1400\\2500\\450\end{bmatrix}$ (Eq.34) and total required final demand $\mathbf{f_d}$ is $\begin{bmatrix}1700\\3800\\600\end{bmatrix}$ (Eq.7). The total required industrial output $\mathbf{x_d}$ is $\begin{bmatrix}4087\\6376\\3600\end{bmatrix}$ (Eq.35). The actual production $\mathbf{x^1}$ after the shock which is limited by capital damage ($\mathbf{x^1}_{\mathbf{cap}}$, Eq.4) and labour constraints ($\mathbf{x^1}_{\mathbf{lab}}$, Eq.5) are $\begin{bmatrix}500\\1000\\700\end{bmatrix}$ (Eq.9).

$$\mathbf{f_{rec}} = \mathbf{f_{ID}} = \hat{\boldsymbol{\alpha}} \times \mathbf{s^0_{cap}} \quad (34)$$

$$\mathbf{x_d} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f_d} \quad (35)$$

Because ($\mathbf{x^1} < x_{\mathbf{d}}$), the remaining industrial production cannot satisfy industrial requirements and final demands at the same time, such limited production results in a supply bottleneck. Import should be added to support basic demand and recovery demand. If import under normal transport conditions is supposed as $\mathbf{y^0_{imp}} = [25 \quad 100 \quad 200]$, then import after the shock $\mathbf{y^1}_{\mathbf{imp}}$ become $[18 \quad 70 \quad 140]$ (Eq.10). Due to Eq.36, we now turn to scenario 1. We have,

$$\begin{cases} \mathbf{x^1} + (\mathbf{y^1_{imp}})' = \begin{bmatrix}500\\1000\\700\end{bmatrix} + \begin{bmatrix}18\\70\\140\end{bmatrix} = \begin{bmatrix}518\\1070\\840\end{bmatrix} \\ \mathbf{Ax^0} = \begin{bmatrix}0.15 & 0.25 & 0.05\\0.2 & 0.05 & 0.4\\0.3 & 0.25 & 0.05\end{bmatrix}\begin{bmatrix}1000\\2000\\1000\end{bmatrix} = \begin{bmatrix}700\\700\\850\end{bmatrix} \end{cases}$$
$$\downarrow$$
$$\mathbf{x^1} + \mathbf{y^1_{imp}} < \mathbf{Ax^0} + \mathbf{f^1_{cd}} \quad (36),$$

In Week 1, available production $\mathbf{x^1}_{\mathbf{rem}}$ is $\begin{bmatrix}518\\1070\\840\end{bmatrix}$ (Eq.12), actual final demand under the new economic balance is $\begin{bmatrix}130\\577\\375\end{bmatrix}$ (Eqs.13 and 14). To repair the industrial capital damage, the rest of final demand ($\mathbf{f^1_{rem}} = \begin{bmatrix}80\\277\\275\end{bmatrix}$, Eq.15), which excludes the basic demand, is used first for industrial capital recovery ($\mathbf{f}^{\mathbf{1}}_{\mathbf{rec}} = \begin{bmatrix} 80 \\ 277 \\ 275 \end{bmatrix}$, Eq.16) and then for other final demands ($\mathbf{f}^{\mathbf{1}}_{\mathbf{others}} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$, Eq.17). The damage fraction for the Week 2 ($\boldsymbol{\alpha}^{\mathbf{1}}$) is $\begin{bmatrix} 0.38 \\ 0.44 \\ 0.12 \end{bmatrix}$ (Eq.18). It should be noticed that when the actual production (including import) of one sector at time *t* is larger than its maximum production capacity, then the actual production of it is equal to the later one.

Full calculations of other weeks are provided in Appendix A. According to our algorithm[6], 14 weeks are needed for the local economic system to recover to the pre-disaster situation. The total indirect impact is estimated as 6182 (Eq.32) and the total flood footprint of this hypothetical flooding is 10532 (Eq.33). Direct economic loss accounts for 41% of the total flood footprint, while the indirect part represents 59%.

5. SENSITIVITY ANALYSIS

Economic consequences of a flood event are sensitive to input data and model parameters. Due to a lack of empirical data to do model validation, different recovery scenarios should be taken into consideration. In this section, the scenario of the hypothetical numerical example referred to in Section 4 is assumed as the reference scenario (Scenario Base), and a series of sensitivity analysis, including alternative labour productivity recovery paths (Scenarios L1-4), various capital recovery paths (Scenarios C1-3), are provided here. Meanwhile, Appendix B also shows sensitivity analysis for the model parameters, such as critical constraint factors (Scenarios R1-3), the basic demands and imports (Scenarios I1-3).

5.1 Alternative labour productivity recovery

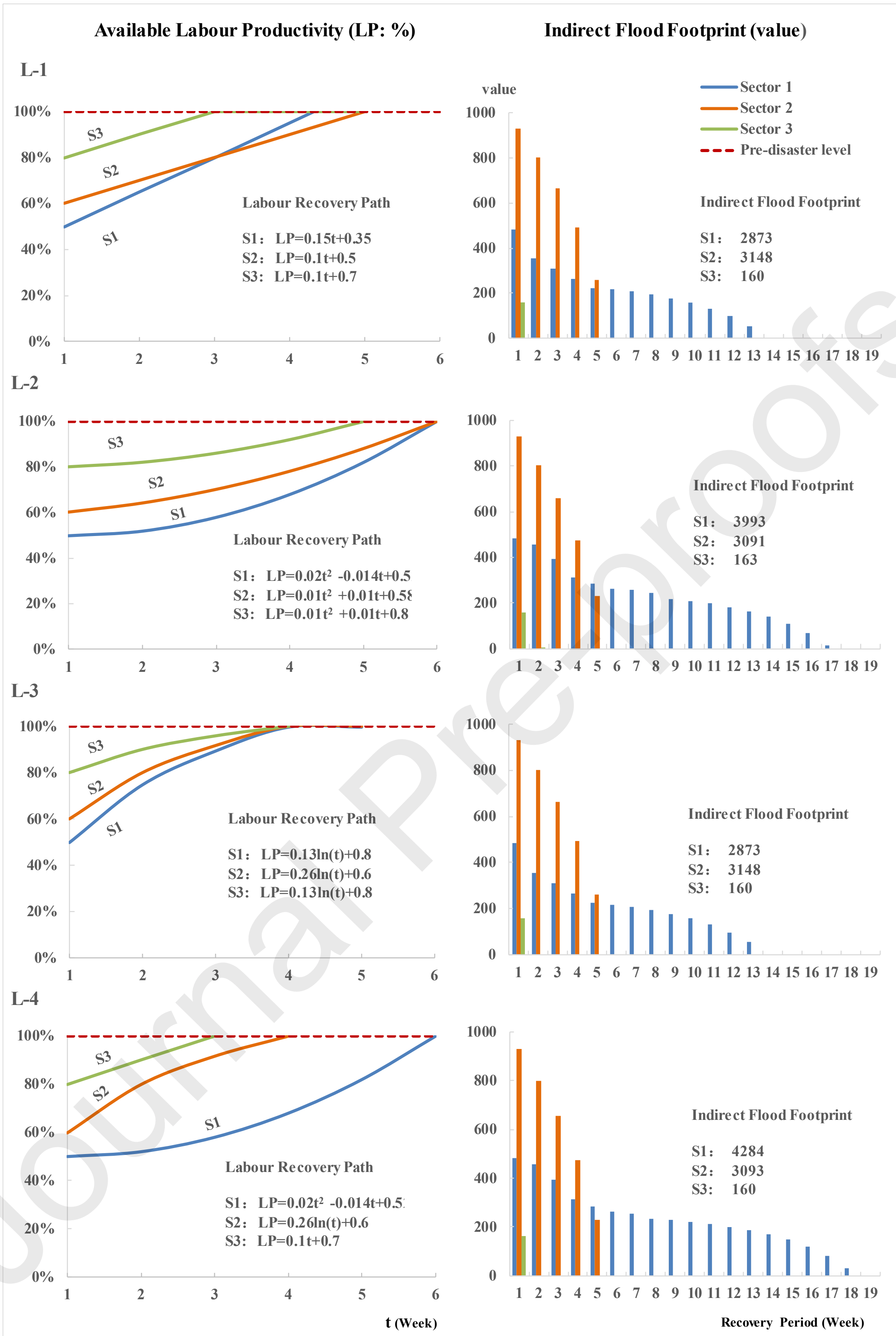
6 The results here are only according to the algorithm proposed in Section 3, not the practical recovery situation of the regional economic system.

The recovery path of labour is an exogenous factor in the model and needs separate attention in each case. Though there is no real statistical data to show how labour is restored in each sector after a flooding event, in general, recovery labour plans depend on the decisions of policymakers and the different reality situations. In section 4, the recovered parts of labour productivity in each stage are assumed as specific data (Table 2). However, apart from this plan, the recovery paths can also be organized as sets of continuous curves. That is to say, the percentage of available labour productivity (LP) of each sector at time t can be according to the different rules, and as such LP is only related to labour parameter (β) in the Flood Footprint Model. To better analyze how a labour restoration plan may influence the recovery process, four new scenarios of labour productivity recovering paths have been selected (Table 3). Scenario L-1 shows linear curves, while Scenario L-2 and L-3 indicate non-linear paths, and L-4 is the mixed plan of both linear and non-linear trends. It should be noted that only the labour restoring paths change among these four scenarios. Other related factors are the same as those in Section 4, while the recovery process of capital productivity can be different in each scenario because this factor is endogenous and no other capital restoration plan is considered here.

Table 3. Results of labour productivity recovery scenarios

Scenario	Recovery Path	Available Labour Productivity (LP)	Recovery Period	Indirect Flood Footprint	Total Flood Footprint
L-1	linear	$\begin{cases} LP_{s1} = 0.15t + 0.35 \\ LP_{s2} = 0.1t + 0.5 \\ LP_{s3} = 0.1t + 0.7 \end{cases}$	14 Weeks	6182	10532
L-2	polynomial	$\begin{cases} LP_{s1} = 0.02t^2 - 0.014t + 0.52 \\ LP_{s2} = 0.01t^2 + 0.01t + 0.58 \\ LP_{s3} = 0.01\,t^2 + 0.01t + 0.8 \end{cases}$	18 Weeks	7247	11598
L-3	logarithmic	$\begin{cases} LP_{s1} = 0.33\ln(t) + 0.5 \\ LP_{s2} = 0.26\ln(t) + 0.6 \\ LP_{s3} = 0.13\ln(t) + 0.8 \end{cases}$	14 Weeks	6182	10532
L-4	mixed plan	$\begin{cases} LP_{s1} = 0.02t^2 - 0.014t + 0.52 \\ LP_{s2} = 0.26\ln(t) + 0.6 \\ LP_{s3} = 0.1x + 0.7 \end{cases}$	19 Weeks	7537	11887

Among these four scenarios, L-2 and L-4 need a longer time to complete restoration and their indirect flood footprints are also higher than others (**Figure 3**). The labour restoration path has a significant impact on the final flood footprint of a flooding event. Meanwhile, L-1 and L-3 have the same indirect flood footprint. Such outcomes can be explained by their actual production, which depends on the minimum of labour and capital production. For L-1 and L-3, despite labour recovery conditions being different, they have the same capital production which is smaller than their labour production, leading to the same actual production in each stage. It is also helpful to explain why the indirect flood footprint of S2 in L-2 and L-4 are almost equal.



Notes: the horizontal axis shows the recovery period and the whole recovery process starts from the first week (the number of the horizontal axis is 1) after the disaster.

Figure 3. Four types of labour productivity recovery curves and their indirect flood footprint. L-1 is the linear recovery curve, L-2, L-3 and L-4 are the non-linear curves.

Another conclusion is that for a certain flood, an indirect flood footprint that resulted from different labour scenarios roughly contains the same pattern, but absolute values widely differ. As shown in Scenario L-2 and L-4, these two scenarios result in the same pattern of indirect flood footprint (right side of the **Figure 3**), in which the S1 lead to the largest indirect economic loss, followed by S2 and S3. However, the values of these three sectors from L-2 are totally different to those from L-4. In particular, the value that from S1 in Scenario L-2 is 300 less than that from L-4, even though their recovery paths of labour productivity are the same. Therefore, although the four labour recovery paths analysed here are all from our own assumptions, influence of labour recovery paths cannot be ignored in the assessment of flood-induced economic impact.

5.2 Alternative capital productivity recovery

In spite of the capital productivity recovery scheme in the Flood Footprint Model being an endogenous element, it can also be recovered through a specified path according to different situations. As a matter of fact, some sectors have their own specific recovery plan, especially infrastructure sectors such as electricity and water supply. These sectors are not only key to the operation of other industries, but are also the basic guarantee for human life. Therefore, compared with other general sectors, such critical sectors are always recovered as priority industries. For example, in the 2016 Leeds flooding in the UK, the West Yorkshire Combined Authority's Investment Committee established a Business Flood Recovery Fund to support businesses from priority sectors: manufacturing, food and drink, low carbon and environmental, financial and professional services, health and life sciences and digital and creative ('Combined Authority', 2016, January 20). Such actions allow priority sectors to be rebuilt earlier than other sectors. It implies that the damaged sectors are not recovered simultaneously during the process of the recovery.

Figure 4 displays four scenarios to better illustrate how these situations influence the total restoration process of the affected economic system. S2 is assumed as the critical sector; the capital recovery scheme of S2 is different to the other two sectors among the scenarios below. In the Base Scenario, all of the three sectors recover from the same time—Week 1 (Section 4). Scenario C-1 assumes that only the capital restoration of S2 is from Week 4; while in Scenario C-2, only S2 is a priority sector, with restoration time occurring in Week 1 and others in Week 4. Scenario C-3 shows the different recovery times of each sector: S1 from Week 6, S2 from Week 4 and S3 from Week 1.

According to the basic conditions of Scenario C-1, during Week 1 to Week 3, the damage fractions of S2 are

$$\alpha_{s2}^{1} = \alpha_{s2}^{2} = \alpha_{s2}^{3} = \alpha_{s2}^{4} = 0.5 \quad (37);$$

recovered capital of S2 are

$$f_{rec\_S2}^{1} = f_{rec\_S2}^{2} = f_{rec\_S2}^{3} = 0 \quad (38).$$

Until in Week 4, S2 starts recovering,

$$f_{rec\_S2}^{4} = \min\left(f_{rec\_s2} - \sum_{t=1}^{3} f_{rec\_s2}^{3}, f_{rem\_S2}^{4}\right) \; (39)$$

$$\alpha_{s2}^{5} = \left(f_{rec\_s2} - \sum_{t=1}^{4} f_{rec\_s2}^{4}\right) ./ s_{cap\_s2}^{0} \quad (40).$$

Scenario C-2 describes that during the first three weeks, the damage ratios of S1 and 3 are:

$$\alpha_{s1}^{1} = \alpha_{s1}^{2} = \alpha_{s1}^{3} = \alpha_{s2}^{4} = 0.4 \quad (41)$$

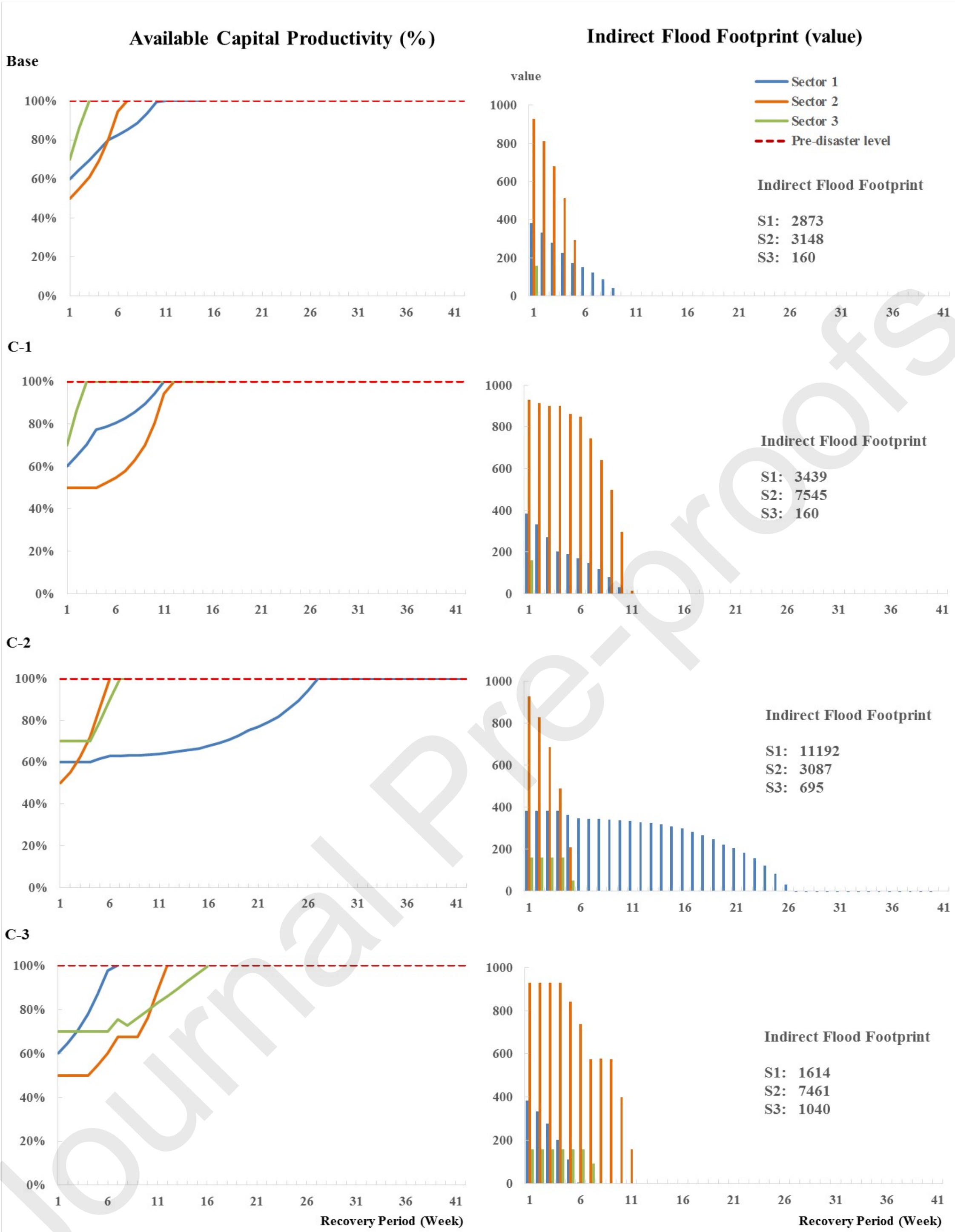
$$\alpha_{s3}^{1} = \alpha_{s3}^{2} = \alpha_{s3}^{3} = \alpha_{s3}^{4} = 0.3 \quad (42)$$

the recovered parts of these two sectors are 0. Until in Week 4, the production of S1 and S3 can be allocated to recovery demand.

Table 4. Results of capital productivity recovery scenarios

Scenario	Capital Recovery Path	Recovery Period	Indirect Flood footprint	Total Flood Footprint
Base	All the sectors from Week 1	14 Weeks	6182	10532
C-1	Only S2 from Week 4	16 Weeks	11144	15494
C-2	Only S2 from Week1, others from Week 4	41 Weeks	14974	19324
C-3	S2 from Week 4, S1 from Week 1, S3 from Week 6	15 Weeks	10116	14466

The outcomes under these four kinds of industrial capital restoration paths are totally different according to our estimation (Table 4). Scenario C-2 requires the longest recovery period (41 weeks) and has the largest total flood footprint (19324); its indirect flood footprint (14974) is almost three times larger than that of the Base Scenario. From the sector perspective, the largest indirect flood footprint of S1, S2 and S3 are shown in Scenario C-2, C-1 and C-3 (**Figure 4**) and such a situation can be explained as an accumulated effect. Taking S2 as an example, in the Scenario Base and C-2, the restoration of S2 is from the beginning stage; in other the two scenarios, S2 remains damaged during the first three weeks without any recovery action. Hence, the accumulated economic loss results in a longer restoration period and larger flood footprint. Even with the extension of the recovery time of one sector, the recovery time and economic loss of the whole economic system will become longer and higher, respectively. This example only focuses on three sectors; if such scenarios occurred in an economic system that includes more sectors, the final impacts will be much larger as the differences of results will be more significant.



Base scheme is the situation that all of the 3 sectors recovered from Week 1. Scenario C-1 assumes that only the capital recovery of S2 is from Week 4; while in Scenario C-2, only S2 is priority sector, which the recovery time is Week 1 and others from Week 4. Scenario C-3 shows the different recovery time of each sector, S1 from Week 1, S2 from Week 4 and S3 from Week 6.

Notes: the horizontal axis shows the recovery period and the whole recovery process starts from the first week (the number of the horizontal axis is 1) after the disaster.

Figure 4. Available capital productivity and indirect flood footprint of three sectors under four types of capital productivity recovery schemes.

6. DISCUSSION

A Rationing Scheme refers to the allocation of available resources, and reflects how the policy-makers or relevant stakeholders prepare for post-disaster recovery. As concluded by Webb et al. (2002) and Corey and Deitch (2011), there is no significant link between the use of post-disaster aid and recovery outcomes in a specific natural disaster. This indicates that direct financial aid from related governments, institutions or NGOs is often deployed inefficiently. It is hard to say which rationing scheme is preferred, but by comparing the different options for resource allocation, policy-makers can select an optimal way to reconstruct the linkages of each industry and recover the pre-disaster economic balance. The Flood Footprint Model facilitates the identification of the critical sectors since it is able to measure the economic impact for each sector. On the basis of the industrial flood footprint, stakeholders will have a comprehensive picture of when and where the economic losses will come from, as well as which sector should be recovered as a priority. Moreover, policy makers or disaster-associated institutions can make more efficient resolutions on how to allocate the available production resources and how to dominate the accessible financial aids or imports. Hence, as the complexity and reality of the response requires a more efficient approach to offer more options of post-disaster economic recovery scenarios, the Flood Footprint Model is one of the best choices in which a variety of sensitivity analysis can be conducted according to various recovery schemes.

Our study offers a broader perspective to disaster risk analysis and management. For investment in flood risk management options, it is critical to identify the 'blind spots' in critical infrastructure and vulnerable sectors in the economic supply chains and social networks. This approach allows for sufficient adaptation to the immediate and long-term damage due to a flood event. Adaption to flood risk is not limited to the area that suffers the direct damage. It also extends to entire socioeconomic networks, and this factor must be considered to minimize the magnitude and probability of cascading damage to regions not directly affected by the flood. At the level of flood risk mitigation responsibility, a flood footprint accounting framework would provide an alternative way to allocate financial responsibility for flood risk mitigation interventions by incorporating the value of all stakeholders' economic capacities in the local/regional/national supply chains. This approach could potentially reduce the financial burden of the government for flood risk management and spread the cost among major stakeholders in the supply chain, based on the 'who benefits, who pays' principle. In other words, if it turns out through a proper flood footprint assessment that organization(s) x or y benefit in a large way from flood defence, then we could consider alternative flood management payment schemes. At a communication level, the flood footprint could be an excellent concept to enhance business and public awareness of the possible damage they may suffer and of the total damage a flood can cause. In addition, we draw attention to an oft-neglected aspect of post-disaster recovery, and that is the role of public authorities.

Although our study proposed many new insights for disaster-related research, there are still several limitations. 1) Sector substitutability is not taken into account in this study. If the substitutability of some local sectors is strong, then the substitution will reduce the impact on the affected production and sectors in the recovery process. 2) We only consider the situation that affected economy will return to pre-disaster level without any changes in technology. Actually, in many disaster-related cases, post-disaster economy will achieve a higher or more advance level, in which technology will be updated or improved during the reconstruction. 3) The Flood Footprint Model established by this research is not able to consider market-based mechanisms. This means that pricing was not taking into account research. However, this factor only plays a relatively small economic role and furthermore, with efficient government management, the prices of most commodities tend to be kept stable during and post disaster. 4) Since political process is too complex to analyse its influence in post-disaster period, issues like actual trade-offs are difficult to consider in this study. 5) Last but not least, it is difficult to verify or validate the results from the Flood Footprint Model, since there is no statistical data about how sectors and economic systems recover after a disaster. Therefore, validation of the results can only be found by comparing them to analyses in related studies. Although several assumptions are made in the Flood Footprint Model, the approach we have used in this paper is to incorporate productivity with capital and labour constraints and adaptive household consumption behaviour. More specific information should be collected and more effort should be made in future research. Since now the model is suitable only for one sudden-onset natural disaster in a single region, it will be continually improved and applied into practical single/multiple disaster events in single/multiple regions.

7. CONCLUSION

Comprehensive analysis of the economic impact of flood disaster on the industrial and economic system has become an urgent and essential part of urban recovery and sustainable development. However, there remain a lack of studies which focus on assessing the indirect economic impacts resulting from floods and, thereafter, providing a common quantitative approach within their assessment. Our paper employs the concept of 'flood footprint' to reflect the total economic impact that is induced by flooding and we have constructed the Flood Footprint Model as an improved tool for indirect economic impact assessment of a sudden-onset natural disaster event. In the light of its different research goals and scope, the model is able to estimate the indirect flood footprint at industrial, regional or economic level within a specific time unit. In contrast to other disaster models, this Flood Footprint Model is more externally oriented and better fits reality. Involving the **a)** basic human demand, **b)** setting the recovery scheme for capital damage as a flexible factor and **c)** linking the degraded productive capacity with labour and capital constraint, make the model more externally oriented and one that better fits the reality of such scenarios. With **d)** considering the model parameters more rationally and accurately through mathematical and logical approaches, the Flood Footprint Model enables us to illustrate the linkages in the rebuilding process among sectors - which are a mystery and a hidden part of the economic system - and provides the indirect economic impacts of each disaster at different time scales according to the scales of flood disasters. This is the final aim and goal of this research.

The Flood Footprint Model has been applied into a hypothetical example, while the mathematical equations and parameters of the model have also been tested through sensitivity analysis based on this hypothetical example. Although there is no any practical meaning behind these assumption data or results, since the hypothetical case we used is not able to guide post-flood recovery in real disaster cases, we can obtain three points from these sensitivity analysis: **i)** one is that different assumptions of variations in the flood footprint model result in various recovery processes of the local economic system. **ii)** If during the recovery process the parameters are not easy to access, such as the recovery curve of labour productivity and the amount of basic demand, then the data used for them in the model must be selected carefully; if there is a real guarantee for post-disaster recovery, like the capital recovery plan, the allocation of available production must be noticed at each stage. **iii)** The last point is that the selection of the rationing scheme should be based on the final aim of the research and the real conditions of the disaster case.

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Appendix A: Calculation of Hypothetical numerical example

Apart from calculation of the hypothetical numerical example in Section 4, other steps are showed as below:

In Week 5,

$$\begin{cases} \mathbf{x}^5 + (\mathbf{y}^5_{\mathbf{imp}})' = \begin{bmatrix} 776 \\ 1741 \\ 1000 \end{bmatrix} \\ \mathbf{Ax^0} + \mathbf{f}^5_{\mathbf{cd}} = \begin{bmatrix} 750 \\ 1000 \\ 950 \end{bmatrix} \\ \mathbf{f_{rec}} - \sum_{t=1}^{4} \mathbf{f}^t_{\mathbf{rec}} = \begin{bmatrix} 871 \\ 898 \\ 0 \end{bmatrix} \end{cases} \tag{A1}$$

$$\downarrow$$
$$Scenario\ 2$$
$$\downarrow$$
$$\mathbf{Ax^0} + \mathbf{f}^5_{\mathbf{cd}} < x^5 + \mathbf{y}^5_{\mathbf{imp}} \leq \mathbf{Ax^0} + \mathbf{f}^5_{\mathbf{cd}} + \left(\mathbf{f_{rec}} - \sum_{t=1}^{4} \mathbf{f}^t_{\mathbf{rec}}\right)$$
$$\downarrow$$
$$Scemario\ 2.1$$

While

$$\mathbf{f}^5_{\mathbf{new}} = \mathbf{x}^5 + \mathbf{y}^5_{\mathbf{imp}} - \mathbf{Ax^0} - \mathbf{f}^5_{\mathbf{cd}} = \begin{bmatrix} 26 \\ 741 \\ 50 \end{bmatrix} \tag{A2}$$

$$\mathbf{f}^5_{\mathbf{rec}} = min\left(\mathbf{f_{rec}} - \sum_{t=1}^{4} \mathbf{f}^t_{\mathbf{rec}}, \mathbf{f}^5_{\mathbf{new}}\ \right) = \begin{bmatrix} 26 \\ 741 \\ 0 \end{bmatrix} \tag{A3}$$

$$\mathbf{f}^5_{\mathbf{others}} = \mathbf{f}^5_{\mathbf{new}} - \mathbf{f}^5_{\mathbf{rec}} = \begin{bmatrix} 0 \\ 0 \\ 50 \end{bmatrix} \tag{A4}$$

$$\boldsymbol{\alpha}^6 = \left(\widehat{\mathbf{s}^{\mathbf{0}}_{\mathbf{cap}}}\right)^{-1} \left(\mathbf{f_{rec}} - \sum_{\mathbf{t}=\mathbf{1}}^{\mathbf{5}} \mathbf{f}^t_{\mathbf{rec}}\right) = \begin{bmatrix} 0.24 \\ 0.03 \\ 0 \end{bmatrix} \tag{A5}$$

……

In Week 14,

$$\mathbf{f}^{14}_{\mathbf{new}} = \mathbf{x}^{14} + \mathbf{y}^{14}_{\mathbf{imp}} - \mathbf{Ax^0} - \mathbf{f}^{14}_{\mathbf{cd}} = \begin{bmatrix} 252 \\ 1000 \\ 50 \end{bmatrix} \tag{A6}$$

$$\mathbf{f}^{14}_{\mathbf{rec}} = min\left(\mathbf{f_{rec}} - \sum_{\mathbf{t}=\mathbf{1}}^{\mathbf{13}} \mathbf{f}^t_{\mathbf{rec}}, \mathbf{f}^{14}_{\mathbf{new}}\ \right) = \begin{bmatrix} 81 \\ 0 \\ 0 \end{bmatrix} \tag{A7}$$

$$\mathbf{f}^{\mathbf{14}}_{\mathbf{others}} = \mathbf{f}^{\mathbf{14}}_{\mathbf{new}} - \mathbf{f}^{\mathbf{14}}_{\mathbf{rec}} = \begin{bmatrix} 171 \\ 1000 \\ 50 \end{bmatrix} \quad (A8)$$

$$\begin{cases} \mathbf{f}_{\mathbf{rec}} - \sum_{t=1}^{14} \mathbf{f}^{t}_{\mathbf{rec}} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \\ \boldsymbol{\alpha}^{\mathbf{15}} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \\ \downarrow \\ \mathbf{x}^{\mathbf{15}} + \mathbf{y}^{\mathbf{15}}_{\mathbf{imp}} > \mathbf{A}\mathbf{x}^{\mathbf{0}} + \mathbf{f}^{\mathbf{15}}_{\mathbf{cd}} + \left(\mathbf{f}_{\mathbf{rec}} - \sum_{t=1}^{14} \mathbf{f}^{t}_{\mathbf{rec}} \right) \quad (A9) \\ \downarrow \\ Scenario\ 2.2 \end{cases}$$

In Week 15, $\mathbf{x}^{\mathbf{15}} = \mathbf{A}\mathbf{x}^{\mathbf{15}} + \mathbf{f}^{\mathbf{0}} = \begin{bmatrix} 1000 \\ 2000 \\ 1000 \end{bmatrix}$ (A10), and the recovery period ends.

Appendix B: Sensitivity Analysis

B.1 Sensitivity to the critical constraint factor

Available capacity of industries in each recovery step is mainly constrained by both labour and capital. However, in many cases, only critical constraint factor (either labour or capital) can affect the available production. For the instance, after the 2017 Hurricane Harvey, nearly 60% of contractors from the construction business reported the problem of skilled labour shortage (Donnelly, 2017, September 18). High demand of commercial construction sectors and a limited quantity of skilled labour led to a difficult recovery in the southern states and the Caribbean. The same situation arose in New Orleans 11years ago, where Hurricane Katrina caused nearly $ 54 billion damage. This was especially noticeable in the industries of gas and oil extraction, industrial chemical manufacturing and petroleum refining. The Federal Reserve Board of Governors reported that compared with previous month, the production from the above industries was reduced 1.7% in the disaster month because of the disruptions of the hurricane (Boone, 2016, August 26; Kliesen, 2017, September 5). It meant that the production capacity of energy sectors was seriously limited by the damaged capital in this event.

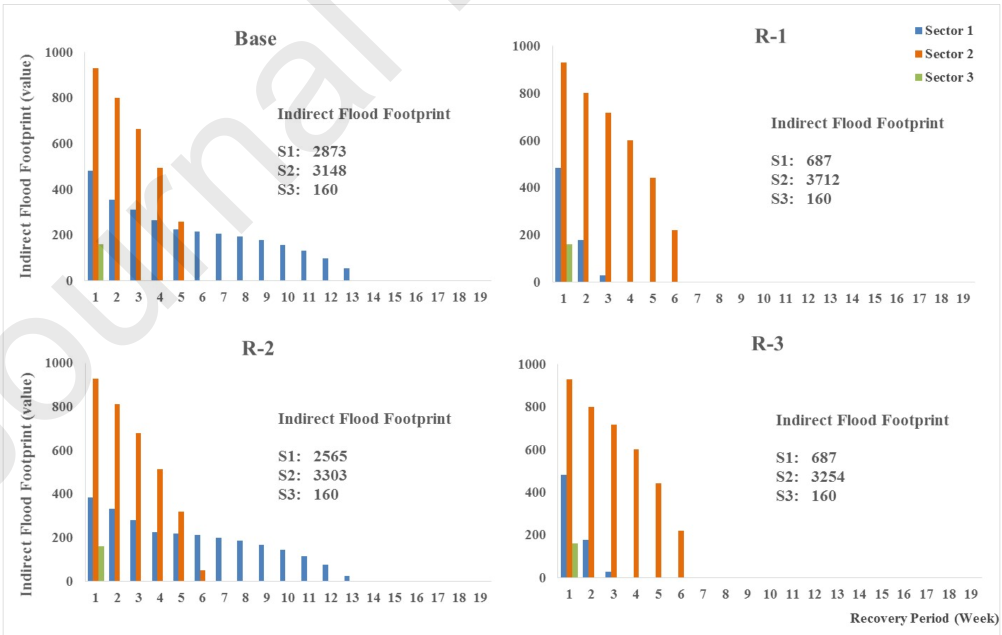
Here, four types of critical constraint factor scenarios are analysed below (Table B.1). In Scenario Base, all the three sectors are constrained by both labour and capital. Scenario R-1 assumes that the production of S1 during the recovery stage is only constrained by labour factor, while in Scenario R-2, the critical constraint factor for S1 is capital. Scenario R-3 shows that the critical constraint factor for S1 is labour and for S2 is capital.

Table B.1. Results of critical constraint factor scenarios

Scenario	Critical Constraint Factor	Recovery Period	Indirect Flood footprint	Total Flood Footprint
Base	3 sectors are constrained by both labour and capital	14 Weeks	6182	10532
R-1	S1 is labour[1]	7 Weeks	4559	8909
R-2	S1 is capital	14 Weeks	6027	10377
R-3	S1 is labour and S2 is capital	7 Weeks	4559	8909

1. If there are no other notifications, the sector is constrained by both labour and capital factor.

Scenarios R-1 and R-3, Scenario Base and R-2 have similar indirect flood footprint trends according to the estimation (**Figure B.1**). Scenarios R-1 and R-3 only need seven Weeks to recover, while Base and R-2 take almost twice as much time to return to pre-disaster economic levels. Meanwhile, R-1 and R-3 resulted in 4559 indirect flood footprints, which is only 75% of that in Base and R-2. In spite of both labour and capital influencing the production capacity of the industry, there is no evidence to show that labour and capital have an immediate relationship through our research. These two variables have their own recovery paths and affect the outcomes in different ways; labour is an exogenous input while capital is an endogenous factor. Distinguishing the critical constraint factors that affect the available production or production capacity of sectors is the basic requirement for economic consequence estimation and analysis of disasters.



Scenario Base shows the original recovery scheme that all the 3 sectors are constrained by both of labour and capital; the critical constraint factor of S1 in Scenario R-1 is labour and in Scenario R-2 is capital. Scenario R-3 shows that the critical constraint factor of Sctor 1 is labour and of S2 is capital.

Notes: the horizontal axis shows the recovery period and the whole recovery process starts from the first week (the number of the horizontal axis is 1) after the disaster.

Figure B.1. Indirect flood footprint of three sectors under the four types of critical constraint factor scenarios.

B.2 Sensitivity to import and Basic demand

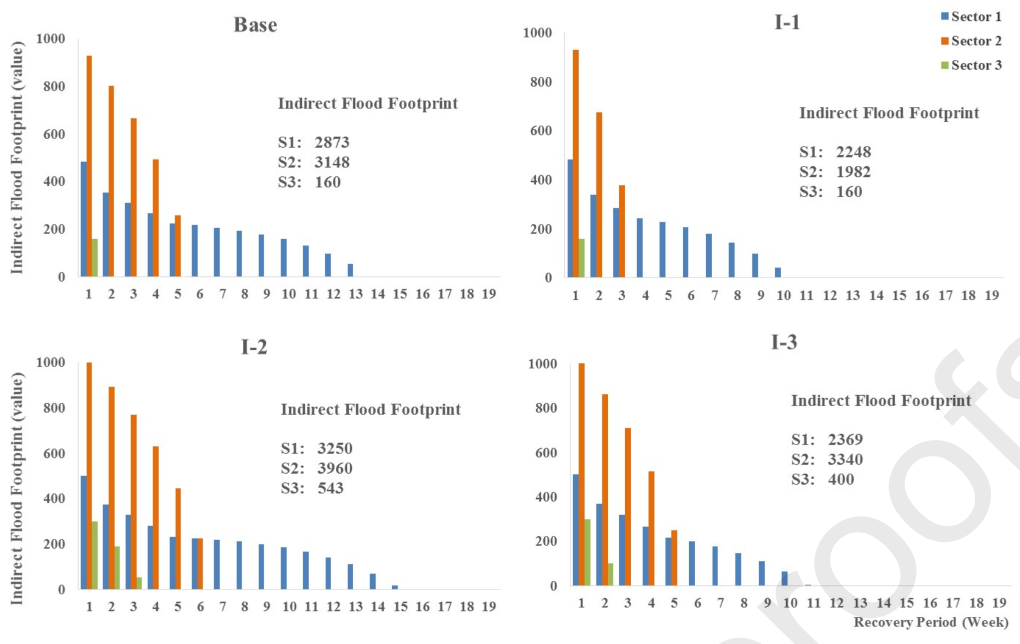
Basic demand and imports at each step decide the percentage of production that is allocated to industrial capital rebuild demands. Basic demand can be different in each stage for one disaster, which will result in a different recovery time and indirect flood footprint. Scenario Base and I-1 illustrate how the basic demand affects the recovery process (Table B.2). It is clear that without a basic demand in each step, the local economic system only takes 11 weeks to rebuild (Scenario I-1), and the recovery period and indirect economic loss of S1 and S2 become shorter. There is no change for S3 because the recovery speed of S3 is only one week. In general, the more production used to support basic demands and the less goods allocated to capital recovery demands, the longer the time required for total recovery.

Table B.2 Results of import and basic demand scenarios

Scenario	Recovery Path	Recovery Period	Indirect Flood footprint	Total Flood Footprint
Base	Both of basic demand and import are considered	14 Weeks	6182	10532
I-1	Without basic demand	11 Weeks	4391	8741
I-2	Without import	16 Weeks	7753	12103

I-3	Import only for capital reconstruction	12 Weeks	6108	10458

Import is a vital supply source for the recovery of an economic system; which part of the process introduces imports has become a question. In some reality cases, the local economic system will never return to pre-disaster levels without imports due to low productivity of the local industries. However, in our hypothetical numerical example, the production of the local economic system can also be satisfied without import. Three import scenarios are compared here: imports in the Base Scenario exist during the whole process; Scenario I-2 do not consider import but rely only on their own production; in Scenarios I-3, imports are only used for industrial capital damage recovery, so that once the capital productivity of the sector returns to a pre-disaster level, import will end. As demonstrated in Table B.2, without import scenario, (I-2) has the longest recovery period and the largest flood footprint. If imports are only allocated to capital reconstruction/recovery demand (I-3), the economic system and each sector will need a shorter time to recover and result in a lower indirect flood footprint (**Figure B.2**), because the reconstruction improves the production capacity. The independence of the economic system determines how import affects total recovery. The higher the independence from external production before the disaster, the lower the possibility for economic system recovery without import; conversely, the higher the amount of imports, the less time required for post-disaster recovery.



Scenario Base shows the original recovery scheme that consider both basic demand and import; I-1 does not include basic demand; I-2 does not include import and in I-3, import is only provided for capital damage recovery demand.

Notes: the horizontal axis shows the recovery period and the whole recovery process starts from the first week (the number of the horizontal axis is 1) after the disaster.

Figure B.2 Indirect flood footprint of three sectors under the four scenarios.

Declaration of interests

■ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: