The economic-wide consequences of natural hazards: an application of a European interregional input-output model

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In this paper, we make first steps with applying a methodology consisting of a hybrid interregional input-output model to assess the economic consequences of large-scale floods for the European economy. The proposed methodology consists of multiple steps. First, a direct loss assessment is conducted in several flood-prone regions, based on simulated floods. Second, the direct losses in capital and labor are translated into the loss in production per sector. Third, the recovery of this production shock is modeled using a hybrid interregional input-output model, combining non-linear programming and input-output modelling. Consequently, when knowing how much production is lost (or gained) in each region, the economic consequences can be assessed. Finally, the model outcome is loss estimation expressed in terms of expected annual damage. To assess these consequences, interregional supply and use tables are used, consisting of 256 different European NUTS2 regions. This data makes it possible to model the indirect losses for both the affected region and the rest of Europe in detail. Results show that regions outside the affected area can have either benefits or losses, depending on the economic relation with the affected region. Consequently, the overall consequences for the European Union are found to be positive for small-scale floods and negative for large-scale floods. This study shows the large potential of interregional modelling and the added value of combining different economic loss estimation approaches into an integrative framework.

Keywords: *natural disaster, macroeconomic effects, input-output modeling*

1. Introduction

In the past decades, the losses of natural disasters have increased significantly and it is expected that this trend will continue in the future (IPCC 2012). In 2005, the global flood losses on coastal cities were estimated to be approximately US$6 billion per year, while it is expected that these losses will increase to up to US$52 billion per year in 2050 (Hallegatte et al. 2013). To cope with this expected increase in disaster losses, a further development of adaptation and mitigation strategies is required to reduce these expected losses. However, for a successful strategy, it is necessary to have an in-depth understanding of the effects of a natural disaster (Meyer et al. 2013).

A vast amount of research has been done to assess a wide-range of disaster losses, varying from the direct and indirect losses, the tangible and intangible losses (see Meyer et al. 2013 for an overview of existing literature) and the short-term (e.g. Li et al. 2013; Hallegatte 2014; Koks et al. 2014a) and long-term effects (e.g. Skidmore and Toya 2002; Coffman and Noy 2012). Nonetheless, disaster research is often still focused on the effects to a single country or region. Both the natural hazard and its economic consequences, however, do not stop at administrative boundaries (Jongman et al., 2014). In a world with increasing economic relations between regions and countries, it can be expected that areas which are not directly hit by the flood will suffer economic losses as well (Okuyama and Santos 2014). In this study, a methodology is introduced which allows for the assessment of the short-run economic effects of a natural disaster for both damaged and non-damaged regions in the European Union (EU).

The methodology introduced will be further referred to as the ERIA (European Regional Impact Assessment) Model. This model is a hybrid dynamic interregional input-output (I-O) model, combining non-linear programming and I-O modeling. Such a framework provides the simplicity of I-O modeling but also allows some more flexibility which is available in computable general equilibrium (CGE) modeling (Oosterhaven et al. 2013). This combination makes it possible to find (i) the production losses in the affected regions and other European regions, (ii) the required production in other regions necessary to take over lost production in the affected regions and (iii) the required production in Europe to satisfy reconstruction demands from the affected regions. Consequently, when knowing how much production is lost (or gained) in each region, the total economic consequences can be assessed. Finally, the model outcome is the estimated economic losses, expressed in terms of Expected Annual Damage (EAD).

The remainder of the paper proceeds as follows. In Section 2, a brief literature overview on disaster modelling is provided, followed by an explanation of the model in Section 3. In Section 4, preliminary results of an application of this model to a flood in the Netherlands are provided. In Section 5, we draw some final conclusions about the feasibility of the model to assess the indirect losses of a natural disaster based on the results of the case study.

2. Disaster modeling

In general, literature that focuses on the economic impacts of disasters distinguishes between two types of losses: stock (direct) losses and flow (indirect) losses (e.g. Bockarjova 2007; Okuyama 2003; Rose 2004). Stock losses can be defined as the direct damages as a result of the flood, which consists of the destruction of both physical and human capital. The estimation of stock losses is often the main focus in the engineering community (e.g. Bouwer et al. 2009; Jongman et al. 2012; Rojas et al. 2013). Flow losses, or more generally called the indirect effects, are considered to be the business interruption losses of the affected industries and the so-called ripple effects towards other (non-affected) economic actors, such as firms, households and governments (Okuyama and Santos 2014). In contrast to the engineering community, flow losses are often the main focus in economic literature (e.g. Hallegatte 2008; Rose and Wei 2013; Okuyama 2014). In addition, the flow losses are commonly subdivided into short-term (up to five years) and long-term (more than five years) effects.

Due to the scope of the paper, we will further concentrate on these indirect effects (flow losses). Different conclusions have been drawn from the estimation of the short-run and long-term economic effects of natural disasters. Skidmore & Toya 2002, for instance, found a positive correlation between natural disasters and long-term economic growth, while Coffman & Noy (2012) and Raddatz (2009) found a negative correlation. Such differences in conclusions can be related almost directly to the limited amount of empirical data available, resulting in difficulties to come to general conclusions (Okuyama and Santos 2014). Moreover, it has been stated that the effects of a disaster might be negative for the affected region, but can be positive for a larger economy in both the short and long term (Albala-Bertrand 2007). In this paper, the latter statement will be tested for the short-term economic effects of a (local) natural disaster in Europe.

Numerous studies have developed models to assess short-run economic effects that occur from a natural disaster within the affected area (e.g. Hallegatte 2008; Rose et al. 2011; Steenge & Bočkarjova 2007). More recently however, more research focuses on assessing the indirect losses outside the affected region in more detail. A few studies have emphasized the interregional effects of natural hazards in general (Okuyama et al. 2004; Okuyama 2010; Ciscar et al. 2014) and earthquakes in specific (Cho et al. 2001; Kim et al. 2002; MacKenzie et al. 2012). The studies that took interregional effects into account show that substantial losses can occur outside the affected regions.

The most commonly used and well-documented approaches in disaster modeling to assess the short-run economic effects are I-O and CGE modeling. Both I-O and CGE models are considered to be well suited for assessing the propagation of an initial shock resulting from a (natural) disaster into the economy (Okuyama and Santos 2014). I-O models, on the one hand, are mainly praised for their simplicity and ability to reflect the economic interdependencies between sectors and regions within an economy through intermediate supply and final demand for deriving higher order effects. CGE models, on the other hand, allow for much more flexibility due to their non-linearity, substitution effects and its ability to reflect price changes. As a result of the different economic mechanisms, the outcomes often differ as well. Due to their linearity and lack of substitution possibilities, I-O models are often considered to overestimate the impacts of a disaster. CGE-models, on the contrary, have the potential to underestimate the impacts because of possible extreme substitution effects and price changes (Rose 2004). Hence, a hybrid approach as proposed in this paper, where the two models are combined might provide the ‘best of both worlds’.

Recently, a number of these hybrid models have been presented (e.g. Hallegatte 2008; Barker and Santos 2010; Oosterhaven et al. 2013; Rose and Wei 2013). The most important difference between these hybrid approach and CGE models is the exclusion of real price effects in these hybrid approaches. Such exclusion can be justified by two reasons: (1) in a post-disaster situation, short-term shortages in supply are more likely to occur due to rationing than due to price effects (Hallegatte 2008) and (2) it is plausible a government might take anti-gouging measures to prevent extreme changes in prices in a disaster aftermath (Rapp 2005). This paper contributes to the current literature by extending such a hybrid approach with an interregional model using supply and use tables on a pan-European scale.

3. Method & data

For the assessment of the short-run economic effects of a natural disaster, multiple modeling steps are required to capture the total indirect effects. First, the direct damages need to be assessed. These direct damages are used to determine the economic disruption of the disaster to the affected sectors and regions. Consequently, this will provide the direct post-disaster economic situation. From the post-disaster situation, the recovery period can start, modeled by using the ERIA model. Finally, after calculating both stock and flow losses, the total economic consequences for each region can be assessed in terms of expected annual damage. The application of the ERIA-model will be tested for a large-scale flood in the Rotterdam port area, one of the largest ports in the world.

3.1. Disaster and economic disruption

A natural disaster can be broadly defined as an impact of the natural environment upon the socioeconomic system (Alexander 1993). Correspondingly, in economic modeling a natural disaster is often translated into an exogenous shock affecting the economy. When applying such an exogenous shock in an economic model, it is important to understand the consequences for the economy after the occurrence of a (natural) disaster. In this respect, we can assume the following will most likely happen to the economy (Rose and Wei 2013):

- Less production in the affected regions due to damaged buildings and infrastructure;
- Less supply and demand to other (non-affected)regions due to reduced production in the industries in the affected regions;
- Additional import demand from the affected regions to other regions to satisfy the demand for products that cannot be satisfied by the affected regions;
- Additional demand from the affected regions for reconstruction needs.

This exogenous shock, however, is often estimated rather arbitrary by taking crude estimates of initial production losses in a specific area (e.g. Rose and Wei 2013; Li et al. 2013). Such an arbitrary estimation is accepted as the main focus in economic literature is often the modeling of the indirect effects and to gain insights in the economic processes. Besides, due to limited empirical data it is often uncertain what 'good' estimates are for an exogenous shock. Nonetheless, as has been shown in literature as well (Hallegatte 2008; Koks et al. in press), the size of the initial disaster losses has a considerable influence on the recovery duration and the size of the indirect losses. Therefore, if data is available, a more detailed assessment of the shock is desirable. The estimation of the direct damages provides a basis for a more detailed disaster shock.

For several types of natural disasters, methods have been developed to assess these direct damages. First off, there is a vast amount of literature which focuses on the assessment of the direct damages of floods (see e.g. Merz et al. 2010; Meyer et al. 2013). For floods, the main approach is the use of susceptibility functions, or depth-damage curves in particular. These depth-damage curves relate the inundation depth of a flood to the damage of a specific land-use or object. These susceptibility functions, however, are applied to other natural hazards as well, such as debris and mud flows, landslides, avalanches and earthquakes. For earthquakes in specific, these functions are often called fragility curves. These fragility curves describe the relationship between the size of earthquake ground motion and damage probability (Shinozuka et al. 2000; Kajitani and Tatano 2014).

By converting the direct damages to a reduction in value-added, the initial production losses due to the disaster can be assessed. This conversion is done by making use of a Cobb-Douglas production function, while assuming constant returns to scale. As shown in Equation [1], a standard Cobb-Douglas function translates the production inputs, capital (K_j) and labor (L_j) into the amount of final goods (Y_j) per sector, where b_j is the total factor productivity per sector and α and β are output elasticities (Cobb and Douglas 1928) .

$$Y_j = b_j K_j^{\alpha} L_j^{\beta} \qquad [1]$$

The assumption of constant returns to scale is especially important to avoid a possible underestimation of the production losses (see Koks et al. in press for an extensive explanation of this process). In standard input-output modelling, capital and labor belong to the value-added part of the model. As such, the Cobb-Douglas function proves to be a tool to translate the direct damages into a reduction in value-added (Y_j in Equation [1]). Consequently, the change in value added (ΔY_j) can be translated into losses in total production (X_j):

$$\sigma_j = \frac{Y_j}{X_j} \; \frac{\Delta Y_j}{Y_j} \qquad [2]$$

As a result, the economic disruption per sector (σ_j) can be seen as the part of the sector in the affected region that is not possible to 'operate'. Therefore, this ‘shock’ will be referred to as a sector inoperability vector, following Santos & Haimes (2004). The next step is to assess by how much the natural disaster affects the production. This can be done by multiplying the total production with the sector inoperability vector, as shown in Equation [1], with X being the vector of the total production and σ as the sector inoperability vector (Equation [2]), where X_t is considered to be the new production level in time period t. In the first run, the new time period is considered to be the post-disaster economic situation. From the post-disaster situation, we can continue to simulate the short-run recovery period.

$$\mathrm{X}^0 \left(1 - \sigma_{\mathrm{t}}\right) = \mathrm{X}_t \qquad [3]$$

3.2. The ERIA-model

The ERIA-Model is a tool to assess the short-run economic effects of a natural disaster for the European economy using an iterative non-linear input-output programming approach, based on a supply and use framework. The ERIA-model can be subdivided into two parts: (i) a basic model, able to reproduce the real situation and (ii) its extension to assess the effects of an economic shock. In the model, we assume a demand determined economy, following the rules of I-O modelling. In other words, demand from all

European regions and the rest of the world has to be satisfied by supply in all separate regions. The representative industries in each region minimize their costs given the demand for products and the technology required to make different products. These technologies describe how industries can make a mix of products and are ´owned´ by the different industries. The mix of products that each industry uses is described in the use table. The mix of products that each industry can make using their technology is described by the supply (make) table. Furthermore, supply is at the lowest possible costs (industries minimize costs) given demand. Thus the objective function of the basic model is the minimization of total production (X_{rs}) over all regions (see Equation [4]) given that supply should be larger or equal to demand (see Equation [5]).

$$Min\, Z_t = \sum_{s=1..15}^{r=1..256} X_{rst} \qquad [4]$$

Running the basic model will return the real situation. For the second part of the ERIA-model, we introduce the following supply constraints:

- Industries are limited in their supply due to a constraint on their maximum capacity.
- There is a regional limit to the supply of industries. This prevents that very small byproducts become main products.
- Due to flooding an additional temporary supply constraints occurs.

And the following demand changes:

- There is additional reconstruction demand in affected regions.
- When demand exceeds maximum supply

In order to still satisfy the demand, industries in the affected region that have not been directly affected by the disaster can increase their supply. However, this may not be enough. Therefore, we allow for additional imports from the known exporting region to the constraint region. Given demand, the supply still takes place at the lowest possible costs. However, there is a trade-off in costs being modelled. Some local firms may start producing byproducts to satisfy the demand for another sectors main product. This may cause extreme additional waste production. In the ERIA-model this is prevented by using a regional maximum supply. As a result, the objective function is still the minimization of total production (X) over the regions given that supply should be larger or equal to demand (Equation [4]), with the extension that additional disaster imports should either be zero or the difference between demand and maximum possible supply (see Equation [8]).

In addition, the model will be iterated over a monthly time period until the pre-disaster economic situation is reached again. By using a sequential model, the reconstruction process becomes dynamic, allowing for a more realistic recovery period. Besides, a multi-period iteration is necessary as it is expected that for large-scale natural hazards, the affected area is not fully recovered in a single time period. For instance, the complete recovery time for New Orleans (Hurricane Katrina in 2005) is expected to take eight to eleven years (Kates et al. 2006). Also, six years after the Kobe earthquake (1995), there were still 12 per cent fewer businesses (Chang 2010).

For the minimization of Equation[4], we define several constraints (Equation [5] - [9]):

$$S_{rpt} \geq \left(U_{rpt} + F_{rpt} + R_{rpt}\right)\left(1 - R_{rpt}\right) - Id_{rpt} + E_{rpt}^{eu} + E_{rpt}^{world} \qquad [5]$$

$$X_{rst} \leq \alpha X_{rs}^{0} \qquad [6]$$

$$R_{rpt} \leq R_{rpt-1} R^{\max} \qquad [7]$$

$$Id_{rpt} = Max\left(0, \left(U_{rpt} + F_{rpt} + R_{rpt}\right)\left(1 - R_{rpt}\right) + E_{rpt}^{eu} + E_{rpt}^{world} - \delta \sum_{s=1..15} A_{rsp}^{make} \alpha X_{rs}^{0}\right) \qquad [8]$$

$$X_{rst} \geq 0 \ , Id_{rpt} \geq 0 \ , R_{rpt} \geq 0 \qquad [9]$$

where:

$$S_{rpt} = \sum_{s=1..15} A_{rsp}^{make} X_{rst} \qquad \text{(supply)}$$

$$U_{rpt} = \sum_{s=1..15} A_{rsp}^{use} X_{rst} \qquad \text{(use)}$$

$$\rho_{rpt} = \frac{I_{rpt}^{eu} + I_{rpt}^{world}}{U_{rpt} + F_{rpt}} \qquad \text{(Import ratio)}$$

$$E_{rpt}^{eu} = \sum_{p=1..58} p_{rpt}^{trade} \qquad \text{(Export with the EU)}$$

First off, the endogenous variables in the model are all assumed to be positive (Equation [9]). Equation [5] states that supply should be larger or equal than the total demand. Sectors often produce secondary products in addition to their primary product. Therefore, a change in demand for one product can result in a change in demand for another product as well. This (waste-) production should be taken into account to be able to end up in a new situation. Factor ρ describes how much of the demand in a specific region is imported from other regions. The variable *Id* defines the required additional import of the affected regions from other regions to satisfy the demand for products which cannot be satisfied due to lost production in the own region (Equation [8]). In Equation [8], δ indicates the regional maximum supply. This parameter prevents a region from producing too much waste production when demand has been reduced due to the disaster. Important to note is that we differentiate in the disaster imports between local and non-local products. In practical terms, this means that, for instance, services provided by the public sector can only be taken over by regions from the same country (local products). Goods produced and services provided by any of the manufacturing sectors, agricultural sector, constructing sector or market services sector can be taken over by any region in the EU that has already existing trade relations with the affected region (non-local products). However, when allowing such import substitutions it is important to realize that substitution might be limited due to specific input requirements (Armington 1969). In this respect, we only allow import substitution if the primary suppliers absolutely cannot produce goods themselves.

Equation [6] states that the production capacity in each region is constrained by the maximum possible overcapacity (α). The maximum possible overcapacity is included because one may assume that industries cannot increase their production unlimitedly. In contrast to, for instance, Hallegatte (2008), the maximum possible overcapacity is not modeled dynamically due to differences in model properties. In this study, it is assumed that overcapacity is possible directly from the beginning. In this respect, the overproduction modeled for the first time-periods after the disaster can be regarded as the usages of the remaining stock, which is proved to be an important factor in disaster modelling (Koks et al. in press; Hallegatte 2014)

Furthermore, it is assumed that only a maximum amount of reconstruction demand R can be satisfied in each time-period (Equation [7]). This equation is based on the assumption that it requires time to reconstruct buildings and infrastructure, as has been shown in several studies (e.g. Kates et al. 2006; Jonkeren and Giannopoulos 2014; Santos et al. 2014). This reconstruction time can be influenced both by financial reasons (e.g. it takes time for economic actors to direct money to reconstruction activities) and a shortfall in production capacity. For instance, after storms in France in 1999, it took several years to reconstruct because there was a shortage of roofers (Hallegatte et al. 2007). However, due to the lack of empirical data, it proves to be challenging to determine 'correct' estimates of the recovery path and time. Therefore, an approach will be taken similar to the Dynamic Inoperability Input-Output Model (DIIM) (Barker and Santos 2010). In the DIIM, it is assumed that sectors decrease their inoperability in each specific time-step. For the ERIA model, the inoperability will not decrease each time-step, but the remaining reconstruction demand (the result, however, is the same). Equation [10] models a similar curve as being used commonly in the DIIM. The maximum recovery time (T^{max}), however, is often declared rather arbitrary. Due to empirical data limitation, this arbitrary approach is currently unavoidable. In the

ERIA model, the maximum recovery time will vary between a few months for a small-scale disaster up to several years for a large-scale disaster.

$$R^{max} = \sqrt{\frac{t}{T^{max}}} - \sqrt{\frac{t-1}{T^{max}}} \qquad [10]$$

After the minimization in each time period *t*, the remaining demand for reconstruction commodities and the new production capacity in the affected regions can be calculated. The new reconstruction needs can be calculated as follows:

$$R_{t+1} = R_{t-1} - R_t \qquad [11]$$

When the new reconstruction demand is known, it is possible to re-assess the amount of damage left and the remaining value added. Consequently, σ can be recalculated using Equation [2] and the new left-over production can be defined:

$$\mathrm{X}_{t+1} = \mathrm{X}^0(1 - \sigma_t) \qquad [12]$$

Knowing the new demand for reconstruction needs and the new production levels, we can repeat Equations [4-12] until $X_{rst} = X_{rs}^0$. As soon as the total reconstruction needs are satisfied, the additional import (*Id*) from the affected regions need to reduce to zero (to end up in the old pre-disaster situation), as zero reconstruction needs implicitly mean that the production capacity is back at its pre-disaster level and the affected region does not require any additional imports from other regions anymore. However, one can assume that a recovered economy does not imply instantly full production yet. Hence, it is plausible that there is still some left-over additional import demand after the reconstruction demand is zero.

3.3. Total economic consequences

When the economy is back at the pre-disaster situation, it is possible to assess the total indirect effects. However, to assess these effects, a few more steps are required. First, the rest-production that can occur due to the demand for certain goods need to be subtracted from the total demand. Because it is rest-production, we assume that it does not provide additional benefits to the producers. Now, the indirect effects (*Γ*) can be computed as the total difference in value added over each time period compared to the initial value added. Or in mathematical notation:

$$\Gamma = \sum_{t} \left(\sum_{j=15} Y_j^0 - \sum_{j=15} Y_{j,t} \right) \qquad [13]$$

Important to note is that the economic consequences can either be negative or positive. If a specific sector is not affected by a reduction in demand for products from the affected region, but is ‘affected’ by an increase in demand due to reconstruction needs, a profit may occur.

Finally, this allows us to assess the expected annual damage for each region in the EU. The expected annual damage can be described as the sum of the expected value of damages that might be caused by a set of disaster events, or as the integral below the probability-loss curve (Grossi and Kunreuther 2005). To derive the integral under the probability-loss curve, a trapezoid approach is taken to assess the expected annual damage, as shown in Equation [14], where *n* is the number of flood events, *D* the total flood damage for the flood event and *P* the probability for the flood event (Koks et al. in press):

$$EAD = \sum_{i=1..n}^{n} \left(\frac{(P_i - P_{i+1}) * (D_{i+1} - D_i)}{2} \right) + (P_i - P_{i+1}) * D_i \qquad [14]$$

3.4. Input data to assess direct damages

As described in Section 2.1, a direct damage assessment for floods is often performed by using the concept of depth-damage functions, which indicate the vulnerability of a specific land-use class by relating the inundation depth to a fraction of the maximum damage of a specific land-use class at that inundation level. Equation [15] shows the function to assess the total direct damage ($\mathit{\Lambda}$) of a flood, where *m* is the amount of land-use classes, *n* the number of land-use cells in the flooded area, *i* the land-use category and *r* the flood depth of a specific cell (Jonkman et al. 2008). Figure 1 shows the most important depth-damage functions used in this study (Koks et al. in press).

$$\Lambda = \sum_{i}^{m} \sum_{r}^{n} \alpha(h_r) \mathit{\Lambda}_i^{max} \eta_{i,r} \qquad [15]$$

where:

$\mathit{\Lambda}_i^{max}$ Maximum damage amount for land use category *i*

$\alpha(h_r)$ Depth-damage function

h_r Hydraulic characteristics of the flood at a particular location

$\eta_{i,r}$ Number of objects of land-use *i* at location *r*

Simulated floods and detailed land-use maps of the study area are used as inputs to arrive at a plausible estimate of the direct damages. The inundation maps in this study are based on flood maps developed by Huizinga (2008) for the harbor area in Rotterdam, with flood return periods ranging between 1/100 and 1/10,000. Important to note is that these inundation maps only cover those areas in the Rotterdam area which are not embanked (e.g. the areas that are not enclosed by dikes). The land-use map is a detailed map that includes 16 industrial land-use classes and 70 land-use classes in total.

3.5. Input data ERIA-model

For the ERIA-model, a European interregional supply and use table for the year 2000 is used, developed by Thissen et al. (2013). This table distinguishes 256 different European regions (NUTS2 level), 59 products (see Appendix I) and 15 sectors (see Appendix II), making a detailed analysis possible. Supply and use tables are considered to be more detailed compared to I-O tables (they often form the basis for the construction of an I-O table). Due to the explicit distinction between commodities and industries, it is possible to take secondary products into account besides the main product which is produced by a specific industry (Temurshoev and Timmer 2011).

4. Preliminary results

This section presents the results of the ERIA model for several large-scale floods in the Rotterdam port area. Table 1 shows the results for both the stock (direct) and flow (indirect) losses of the three floods that are considered for the region the case-study area is situated (the region of South-Holland). In line with the results found in Koks et al. (in press), both the ratio flow/stock and the indirect losses increases with the severity of the flood. In this study, however, the indirect effects are approximately twice as little compared to Koks et al. (in press), which are computed by using a single-region model. As the size of the disaster and determination of the shock is exactly the same in both studies, this shows that allowing for substitution with other regions significantly lower the losses.

Table 1: Total stock and flow losses for the region of South-Holland for each return period (in millions Euro)

	Stock losses	Flow losses	Ratio flow/stock
1/100	442	205	0.46
1/1,000	761	498	0.65
1/10,000	1880	1266	0.67

Figure 1 shows the total production change for every region in the EU for the 1/1,000 flood over the whole reconstruction period. As expected, the losses are the highest in the flooded region. Actually, the flooded region is the only region that has an overall loss. Nonetheless, some interesting results can be observed from Figure 1. To begin with, we can clearly observe a 'ripple-effect' through the EU. The direct neighboring regions benefit the most from the flood in South-Holland (The Netherlands and Belgium can be clearly seen in the figure). Additionally, the Figure also clearly shows the ‘redistribution’ effect of the flood. Besides the direct surround regions, several other regions such as the regions of Paris, Barcelona and Madrid gain a substantial increase in production during the reconstruction period. This redistribution effect clearly demonstrates the potential of the European Union to satisfy demand for products, even though a specific region is partly out of business.

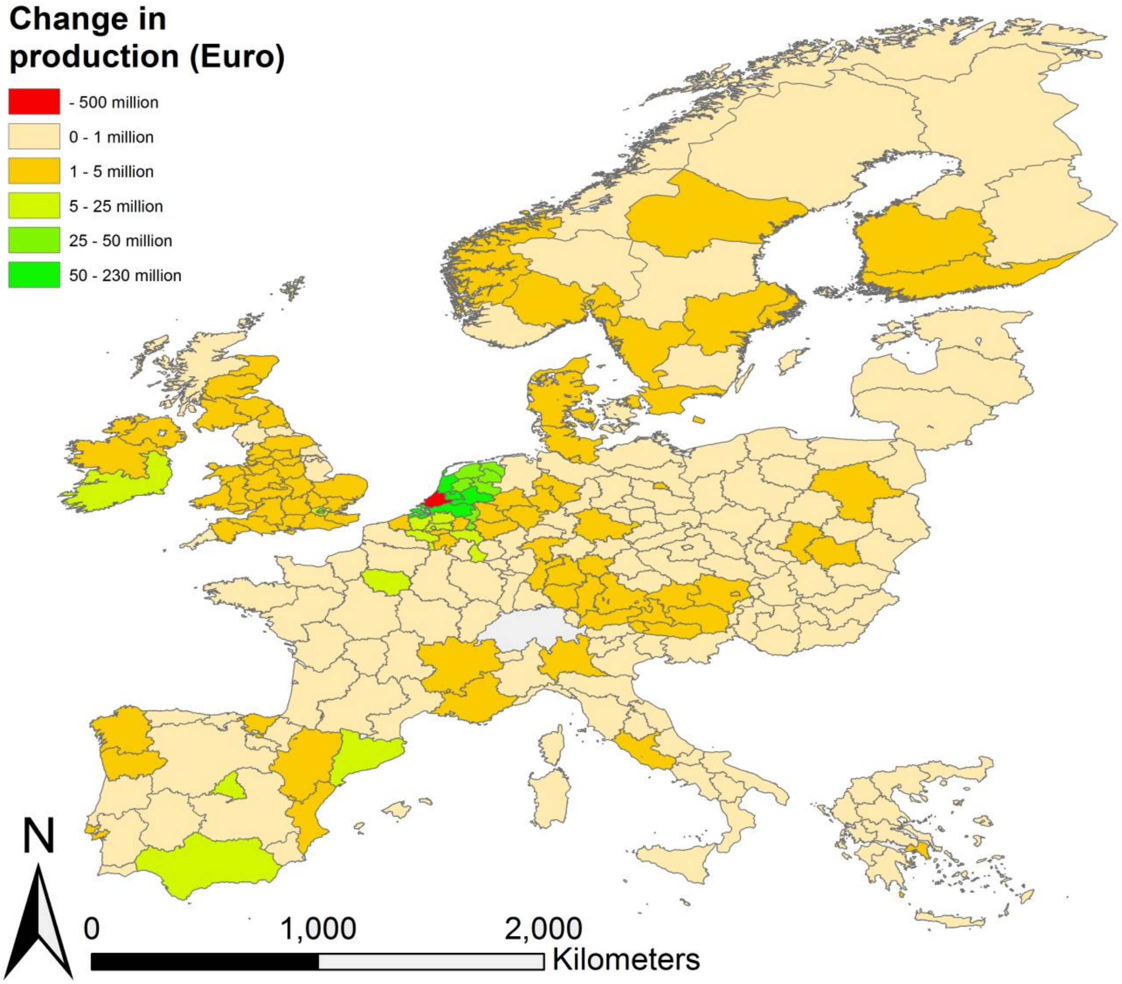

Figure 1: Total production change per region in the European Union due to the 1/1,000 flood in the region of South-Holland

Table 2 shows the results for the region of South-Holland on a sectoral level. As can be seen from the table, most sectors suffer a loss from the flood, except for the construction and distribution sector. The construction sector gain benefits due to increased demand because of reconstruction needs. The distribution sector seems to benefit from both the additional demand for reconstruction and the required additional imports from other regions to satisfy the remaining demand in the affected region.

Table 2: Total indirect effects per sector for the region of South-Holland for a 1/1,000 flood. Note: a '+' indicates benefits, a '-' indicates losses.

Sector	Total effect (in million Euro)
Agriculture	-34,0
Mining ,quarrying and energy supply	-21,2
Food, beverages and tobacco	-18,1
Textiles and leather etc.	-28,4
Coke, refined petroleum, nuclear fuel and chemicals	-40,0
Electrical and optical equipment	-40,0
Other manufacturing	-90,7
Construction	38,8
Distribution	470,9
Hotels and restaurants	-32,5
Transport, storage and communications	-128,1
Financial intermediation	3,1
Real estate, renting and business activities	-237,6
Non-Market Services	-340,9

5. Concluding remarks

This paper presented a non-linear input-output programming approach, using interregional supply and use tables, to assess the effects of a natural disaster on the EU economy. To test the model, three flood events in the port of Rotterdam have been analyzed. By using simulated floods, a realistic estimate of the possible pan-European consequences of a flood is provided. In addition, by combining a non-linear programming approach with interregional input-output modeling, we have created a framework that combines both the benefits of I-O modeling (simplicity) and CGE modeling (model flexibility, substitution possibilities).

Results show that most of the regions outside the affected area are not affected by the natural disaster. Most of the regions gain benefits from the flood by taking over some of the lost production or by satisfying reconstruction demand from the affected region. Some regions suffered losses, mainly due to trade relations with the manufacturing sector in the affected region. Consequently, the size of the flood has an important effect on the overall consequences for Europe. For a small-scale flood, the substitution of production and the additional reconstruction demand results in benefits on a pan-European scale. For a large-scale flood, results show that non-affected regions are unable to fully offset the lost production in the affected region, resulting in an overall loss for Europe.

Due to the relative few input requirements and a basic modeling approach, the ERIA model proves to be a suitable tool for policy makers to assess the indirect effects of a natural disaster. Even though the ERIA-model is now based on the use of supply and use tables, easier available IO-tables as input are possible as well. In this study, a large-scale flood is used as a case study to demonstrate the applicability of the model. With relative ease, however, this can be changed into a different natural hazard.

Nonetheless, more research is required to improve the model. First, more research is required regarding the recovery period of different industries and infrastructure to reduce uncertainty in the model. Due to the lack of empirical data, this is still a challenge. Second, relocation of industries is not taken into account in this study. After a severe natural disaster, it might be expected that several firms relocate as an adaptation measure to reduce the future risk of being affected by a flood. Finally, the model only analyses the short-run effects of a disaster. Because the long-term effects can put the economic impact in a different perspective, considering both the short-term and long-term effects in the future is required.

References

Albala-Bertrand JM (2007) Globalization and localization: an economic approach. Handb. Disaster Res. Springer, pp 147–167

Albala-Bertrand JM (2013) Disasters and the Networked Economy. Routledge

Alexander DE (1993) Natural disasters. UCL Press Limited, University College London

Armington PSS (1969) A Theory of Demand for Products Distinguished by Place of Production. Staff Pap Monet Fund 159–178.

Barker K, Santos JR (2010) Measuring the efficacy of inventory with a dynamic input--output model. Int J Prod Econ 126:130–143. doi: 10.1016/j.ijpe.2009.08.011

Bockarjova M (2007) Major disasters in modern economies: An input-output based approach at modelling imbalances and disproportions. University of Twente

Bouwer LM, Bubeck P, Wagtendonk a. J, Aerts JCJH (2009) Inundation scenarios for flood damage evaluation in polder areas. Nat Hazards Earth Syst Sci 9:1995–2007. doi: 10.5194/nhess-9-1995-2009

Chang SE (2010) Urban disaster recovery: a measurement framework and its application to the 1995 Kobe earthquake. Disasters 34:303–327. doi: 10.1111/j.1467-7717.2009.01130.x

Cho S, Gordon P, Moore II, et al. (2001) Integrating transportation network and regional economic models to estimate the costs of a large urban earthquake. J Reg Sci 41:39–65.

Ciscar JC, Feyen L, Soria A, et al. (2014) Climate Impacts in Europe. Results from the JRC PESETA II Project.

Cobb CW, Douglas PH (1928) A theory of production. Am Econ Rev 139–165.

Coffman M, Noy I (2012) Hurricane Iniki: measuring the long-term economic impact of a natural disaster using synthetic control. Environ Dev Econ 17:187–205. doi: 10.1017/S1355770X11000350

Grossi P, Kunreuther H (2005) Catastrophe Modeling: A New Approach to Managing Risk.

Hallegatte S (2014) Modeling the role of inventories and heterogeneity in the assessment of the economic costs of natural disasters. Risk Anal 34:152–167.

Hallegatte S (2008) An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina. Risk Anal 28:779–99. doi: 10.1111/j.1539-6924.2008.01046.x

Hallegatte S, Green C, Nicholls RJ, Corfee-Morlot J (2013) Future flood losses in major coastal cities. Nat Clim Chang 3:802–806.

Hallegatte S, Hourcade J-C, Dumas P (2007) Why economic dynamics matter in assessing climate change damages: illustration on extreme events. Ecol Econ 62:330–340.

IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-. 582 pp.

Jongman B, Kreibich H, Apel H, et al. (2012) Comparative flood damage model assessment: towards a European approach. Nat Hazards Earth Syst Sci 12:3733–3752. doi: 10.5194/nhess-12-3733-2012

Jonkeren O, Giannopoulos G (2014) Analysing critical infrastructure failure with a resilience inoperability input–output model. Econ Syst Res 26:39–59. doi: 10.1080/09535314.2013.872604

Jonkman SN, Bočkarjova M, Kok M, Bernardini P (2008) Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. Ecol Econ 66:77–90. doi: http://dx.doi.org/10.1016/j.ecolecon.2007.12.022

Kajitani Y, Tatano H (2014) Estimation of production capacity loss rate after the great east japan earthquake and tsunami in 2011. Econ Syst Res 26:13–38. doi: 10.1080/09535314.2013.872081

Kates RW, Colten CE, Laska S, Leatherman SP (2006) Reconstruction of New Orleans after Hurricane Katrina: a research perspective. Proc Natl Acad Sci U S A 103:14653–60. doi: 10.1073/pnas.0605726103

Kim TJ, Ham H, Boyce DE (2002) Economic impacts of transportation network changes: Implementation of a combined transportation network and input-output model. Pap Reg Sci 81:223–246.

Koks EE, Bockarjova M, De Moel H, Aerts JCJH (in press) Development and sensitivity analysis of an integrative flood risk model for port regions. Risk Anal.

Li J, Crawford-Brown D, Syddall M, Guan D (2013) Modeling Imbalanced Economic Recovery Following a Natural Disaster Using Input-Output Analysis. Risk Anal.

MacKenzie C a., Santos JR, Barker K (2012) Measuring changes in international production from a disruption: Case study of the Japanese earthquake and tsunami. Int J Prod Econ 138:293–302. doi: 10.1016/j.ijpe.2012.03.032

Merz B, Kreibich H, Schwarze R, Thieken A (2010) Review article“ Assessment of economic flood damage.”Nat Hazards Earth Syst Sci 10:1697–1724.

Meyer V, Becker N, Markantonis V, et al. (2013) Review article: Assessing the costs of natural hazards â€“ state of the art and knowledge gaps. Nat Hazards Earth Syst Sci 13:1351–1373. doi: 10.5194/nhess-13-1351-2013

Okuyama Y (2003) Economics of natural disasters: A critical review. Res Pap 12:20–22.

Okuyama Y (2014) Disaster and economic structural change: case study on the 1995 kobe earthquake. Econ Syst Res 26:98–117. doi: 10.1080/09535314.2013.871506

Okuyama Y (2010) Globalization and Localization of Disaster Impacts: An Empirical Examination. CEFifo Forum. pp 56–66

Okuyama Y, Hewings GJD, Sonis M (2004) Measuring economic impacts of disasters: interregional input-output analysis using sequential interindustry model. Model Spat Econ Impacts Disasters 77–101.

Okuyama Y, Santos JR (2014) DISASTER IMPACT AND INPUT--OUTPUT ANALYSIS. Econ Syst Res 26:1–12.

Oosterhaven J, Bouwmeester MC, Nozaki M (2013) The impact of production and infrastructure shocks: A non-linear input-output programming approach, tested on a hypothetical economy. 60th NARSC Conf.

Raddatz C (2009) The wrath of God: macroeconomic costs of natural disasters.

Rapp GC (2005) Gouging: Terrorist attacks, hurricanes, and the legal and economic aspects of post-disaster price regulation. Ky LJ 94:535.

Rojas R, Feyen L, Watkiss P (2013) Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. Glob Environ Chang 23:1737–1751. doi: 10.1016/j.gloenvcha.2013.08.006

Rose A (2004) Economic principles, issues, and research priorities in hazard loss estimation. Model. Spat. Econ. impacts disasters

Rose A, Liao S-Y, Bonneau A (2011) Regional Economic Impacts of a Verdugo Scenario Earthquake Disruption of Los Angeles Water Supplies: A Computable General Equilibrium Analysis. Earthq Spectra 27:881–906.

Rose A, Wei D (2013) ESTIMATING THE ECONOMIC CONSEQUENCES OF A PORT SHUTDOWN: THE SPECIAL ROLE OF RESILIENCE. Econ Syst Res 25:212–232.

Santos JR, Haimes YY (2004) Modeling the Demand Reduction Input-Output (I-O) Inoperability Due to Terrorism of Interconnected Infrastructures*. Risk Anal 24:1437–1451.

Santos JRJ, Yu KKDS, Pagsuyoin SAT, Tan RR (2014) Time-varying disaster recovery model for interdependent economic systems using hybrid input–output and event tree analysis. Econ Syst Res 26:60–80. doi: 10.1080/09535314.2013.872602

Shinozuka M, Feng MQ, Lee J, Naganuma T (2000) Statistical analysis of fragility curves. J Eng Mech 126:1224–1231.

Skidmore M, Toya H (2002) Do natural disasters promote long-run growth? Econ Inq 40:664–687.

Steenge AE, Bočkarjova M (2007) Thinking about Imbalances in Post-catastrophe Economies: An Input--Output based Proposition. Econ Syst Res 19:205–223.

Temurshoev U, Timmer MP (2011) Joint estimation of supply and use tables. Pap Reg Sci 90:863–882. doi: 10.1111/j.1435-5957.2010.00345.x

Thissen M, van Oort F, Diodato D, Ruijs A (2013) Regional Competitiveness and Smart Specialization in Europe: Place-based Development in International Economic Networks. Edward Elgar Publishing

Appendix I: Products and services

	Product or service	Local (L) /Non-local (NL)
P1	Products of agriculture, hunting and related services	NL
P2	Products of forestry, logging and related services	NL
P3	Fish and other fishing products; services incidental of fishing	NL
P4	Coal and lignite; peat	NL
P5	Crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying	NL
P6	Uranium and thorium ores	NL
P7	Metal ores	NL
P8	Other mining and quarrying products	NL
P9	Food products and beverages	NL
P10	Tobacco products	NL
P11	Textiles	NL
P12	Wearing apparel; furs	NL
P13	Leather and leather products	NL
P14	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	NL
P15	Pulp, paper and paper products	NL
P16	Printed matter and recorded media	NL
P17	Coke, refined petroleum products and nuclear fuels	NL
P18	Chemicals, chemical products and man-made fibres	NL
P19	Rubber and plastic products	NL
P20	Other non-metallic mineral products	NL
P21	Basic metals	NL
P22	Fabricated metal products, except machinery and equipment	NL
P23	Machinery and equipment n.e.c.	NL
P24	Office machinery and computers	NL
P25	Electrical machinery and apparatus n.e.c.	NL
P26	Radio, television and communication equipment and apparatus	NL
P27	Medical, precision and optical instruments, watches and clocks	NL
P28	Motor vehicles, trailers and semi-trailers	NL
P29	Other transport equipment	NL
P30	Furniture; other manufactured goods n.e.c.	NL
P31	Secondary raw materials	NL
P32	Electrical energy, gas, steam and hot water	NL
P33	Collected and purified water, distribution services of water	NL
P34	Construction work	NL
P35	Trade, maintenance and repair services of motor vehicles and motorcycles; retail saleof automotive fuel	L
P36	Wholesale trade and commission trade services, except of motor vehicles and motorcycles	L

	Product or service	Local (L) /Non-local (NL)
P37	Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods	L
P38	Hotel and restaurant services	L
P39	Land transport; transport via pipeline services	L
P40	Water transport services	L
P41	Air transport services	L
P42	Supporting and auxiliary transport services; travel agency services	L
P43	Post and telecommunication services	L
P44	Financial intermediation services, except insurance and pension funding services	L
P45	Insurance and pension funding services, except compulsory social security services	L
P46	Services auxiliary to financial intermediation	L
P47	Real estate services	L
P48	Renting services of machinery and equipment without operator and of personal and household goods	L
P49	Computer and related services	NL
P50	Research and development services	NL
P51	Other business services	NL
P52	Public administration and defence services; compulsory social security services	L
P53	Education services	L
P54	Health and social work services	L
P55	Sewage and refuse disposal services, sanitation and similar services	L
P56	Membership organisation services n.e.c.	L
P57	Recreational, cultural and sporting services	L
P58	Other services	L
P59	Private households with employed persons	L

Appendix II: Sectors

	Sector
S1	Agriculture
S2	Mining ,quarrying and energy supply
S3	Food, beverages and tobacco
S4	Textiles and leather etc.
S5	Coke, refined petroleum, nuclear fuel and chemicals
S6	Electrical and optical equipment
S7	Transport equipment
S8	Other manufacturing
S9	Construction
S10	Distribution
S11	Hotels and restaurants
S12	Transport, storage and communications
S13	Financial intermediation
S14	Real estate, renting and business activities
S15	Non-Market Services