Environmental Research Letters

LETTER

The macroeconomic impacts of future river flooding in Europe

E E Koks, M Thissen, L Alfieri, H De Moel, L Feyen, B Jongman and J C J H Aerts

1 Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
2 Environmental Change Institute, University of Oxford, Oxford, United Kingdom
3 Netherlands Environmental Assessment Agency, The Hague, The Netherlands
4 European Commission, Joint Research Centre, Ispra, Italy
5 World Bank Group, Washington DC, United States of America
6 Author to whom any correspondence should be addressed.

E-mail: elco.koks@vu.nl

Keywords: climate change, economic impacts, river flooding, disaster risk

Supplementary material for this article is available online

Abstract

The economic impacts of disasters can reach far beyond the affected regions through interconnected transboundary trade flows. As quantification of these indirect impacts is complex, most disaster risk models focus on the direct impacts on assets and people in the impacted region. This study explicitly includes the indirect effects via regional economic interdependencies to model economic disaster losses on a continental scale, exemplified by river flooding in Europe. The results demonstrate that economic implications go beyond the direct damages typically considered. Moreover, we find that indirect losses can be offset by up to 60% by economic actors through finding alternative suppliers and markets within their existing trade relations. Towards the future, increases in economic flood losses (up to 350%) can be expected for all global warming scenarios. Indirect losses rise by 65% more compared to direct asset damages due to the increasing size of future flood events, making it more difficult to offset losses through alternative suppliers and markets. On a sectoral level, future increases in losses are highest for commercial services (~980%) and public utilities (~580%). As the latter are predominately affected through cascading effects, this highlights how interdependencies between economic actors could amplify future disaster losses.

1. Introduction

In Europe, large-scale floods occur almost every year and, due to climate change, their frequency and magnitude is expected to increase (Kundzewicz et al 2014, Forzieri et al 2016, Alfieri et al 2018). Floods can affect several river basins or countries at the same time, leading to highly correlated direct damages (e.g. to buildings and infrastructure) across European countries (Jongman et al 2014). Floods, however, also give rise to indirect economic effects, such as the cost of economic recovery after a flood, or production losses in non-flooded areas propagated through supply chain networks (Levermann 2014, Dottori et al 2018, Willner et al 2018). Hallegatte (2008), for instance, shows that including the indirect economic effects of Hurricane Katrina resulted in an increase of total losses of up to 40% in the affected region. Other studies show that indirect losses can even become twice as large as the direct damages (Koks et al 2015, Dottori et al 2018). Indirect losses become increasingly important because of the growth in regional production processes based on the Just-In-Time revolution in logistics and supply chains, in combination with (customized) demand and trade structures in Europe that stretch far beyond the flooded region (McCann 2010, Chen et al 2018). As a result, analyzing both the direct and indirect losses on a pan-European scale will result in a more complete picture of the possible total flood impacts.

Only approximate estimates of indirect economic losses within Europe have so far been presented (Ciscar et al 2011, 2014). Recent advances in the simulation of indirect losses (Hallegatte 2014, Wenz et al 2014, Oosterhaven and Bouwmeester 2016) have paved the way for investigating the systemic effects of disaster risk on a wider scale. This study presents a
comprehensive flood risk analysis that explicitly includes regional economic interdependencies on a continental scale. The economic consequences of floods are assessed by analyzing direct local consequences as well as indirect effects across 270 sub-national NUTS2 regions (figure S1 is available online at stacks.iop.org/ERL/14/084042/mmedia), both on a regional and sector level. The impacts of floods under climate change are calculated for an ensemble of climate projections (Alfieri et al. 2017) (table S1), resulting in 6885 unique flood events causing economic losses in Europe (Methods). Indirect impacts are calculated by using a recursive dynamic multi-regional supply and use model: the multi regional impact assessment (MRIA) model (Koks and Thissen 2016). The MRIA model is a state-of-the-art multi-regional economic model, capable of estimating a new economic equilibrium in the short-term disaster aftermath (up to 1 year, figure S2). The model allows for analyzing disruptions to production capabilities, and can simulate market adjustments due to changes in the availability of supply and demand (Methods). The model is therefore well equipped to assess the economy-wide consequences of a natural disaster shock (e.g. a flood) on a pan-European scale. As modeling a future structure of the economy is difficult (especially on such a detailed scale), we keep the economy constant on the structure as of 2013 and focus specifically on the potential impacts of climate change. Moreover, in the presentation of our results we excluded direct damages to residential properties as we primarily focus on the economic impacts to and from producing (economic) sectors.

2. Methods

2.1. Flood event set

We use the Lisflood distributed hydrological model to run 130+ years of daily atmospheric variables starting in 1970 for seven independent climatic projections based on the representative concentration pathways of 8.5 W m⁻². Table S1 outlines in which year certain degrees of global warming are expected in each climate model. The baseline year for this study is 2010. The set of climate models are selected as a representative range of outcomes for future climate change, including high and low climate sensitivity, different bias in the baseline precipitation climatology, and different global patterns of precipitation change (Alfieri et al. 2017). Lisflood is a hybrid between a conceptual and a physically-based rainfall-runoff model combined with a routing module to convey the streamflow’s through the river network. It has been specifically developed to simulate the hydrological processes in large river basins (De Roo et al. 2001) and it currently underpins the operational runs of EFAS and GloFAS, the European and Global systems for flood early warning of the Copernicus Emergency Management Service. For this work, Lisflood is set up on the global domain excluding Antarctica at 0.5° resolution (~55 km at the equator).

Output time series of daily discharges at each grid point and climate projection are analyzed to link peak values to their statistical recurrence intervals. We fit Gumbel extreme value distributions on the series of annual maxima in the baseline period, using the method of L-Moments, and then assigned to each peak discharge in the entire simulation period the corresponding return period in years (i.e. the inverse of the annual probability of occurrence). The resulting dataset is compared with the FLOPROS (Scussolini et al. 2016) dataset of flood protection standards, to identify ‘flood events’ as all the occurrences with a return period of the peak discharge larger than the corresponding protection standards. Gridded data on flood events are then grouped by day to identify 6885 unique large-scale (upstream areas larger than 5000 km²) flood events causing economic losses in Europe. It should be noted that the losses for each event are calculated independently and not consecutively throughout the years. This means that we omit both the chance that a new flood event in a region occurs when still recovering from the previous and the chance of possible interactions between compound events. These possible interactions with other events are not considered in this study to allow us to improve our understanding of the economic dynamics of single flood events first.

2.2. Asset damages

Asset damages from floods are estimated through a two-step approach proposed by Alfieri et al. (2015). First, we use a database of global flood hazard maps (Dottori et al. 2016) to estimate direct flood damages for a set of six constant return periods (10, 20, 50, 100, 200, 500 years). To this end, depth-damage curves (Huisinga et al. 2017) specific for country, land-use, and economic sector are used to estimate damage for each constant flood scenario at horizontal resolution of 30 arc-second (~900 m at the Equator). Maps of potential impact per sector are aggregated at the resolution of the hydro-climatic forcing of 0.5° using a physically based approach which assigns flooded areas to the grid point of the causative inflow hydrograph at coarser resolution (Alfieri et al. 2015). Second, the damage of each flood event simulated by the seven considered climate projections is estimated by interpolating linearly along the two closest return periods previously calculated. To increase the robustness of flood damage estimates that inherently show high variability in space and time, asset damages are aggregated at NUTS2 level and over 30 year windows, corresponding to the baseline period and to the three selected global warming levels (i.e. 1.5°, 2° and 3°).
2.3. From asset damages to production losses

To be able to model the economic losses, one needs to estimate how production capacity initially reduces for each sector in a region that is affected during the flood event. To do so, several steps are taken, similar to Dottori et al. (2018). Firstly, we estimate for each of the three sectors (industry, commercial, agriculture) what the total value of exposed assets is in any of the NUTS2 regions. We assume that each industry requires a certain stock of assets to be able to produce output. Secondly, the total value of exposed assets is calculated by multiplying the total area of each of the sectors within a NUTS2 area by their maximum possible damages. Here we assume that the maximum possible damage equals to full reconstruction cost. Maximum possible damage values for each sector are estimated per country (Huizinga et al. 2017). Finally, we divide the damages for each sector by the total asset value for each sector. This ratio is assumed to be the initial reduction in production capacity in the direct post-disaster aftermath. We acknowledge that this approach is rather simplistic. Nonetheless, we followed this simple approach as it proves to be difficult to do this with more spatial detail and on a higher resolution. Land-use maps still do not distinguish between different industry types, and geospatial maps showing exact locations of industrial activity are simply not readily available.

2.4. Modeling economic losses

A wide range of models has been developed (and applied) recently to estimate the macroeconomic impacts of extreme events on various scales. This varies from more traditional input–output models, to various forms of Computable General Equilibrium models (Carrera et al. 2015). In additional, we have seen a wide-range of new models being developed in recent years, such as the Acclimate model (Otto et al. 2017) and the MaGE model (Fouré et al. 2013). Similar to this study, there is a general tendency to improve the spatial resolution and to include transboundary trade effects. The MRIA model (Koks and Thissen 2016) allows us to analyze the consequences within regions as well as sector-specific decrease in production capabilities that are not present in most existing input–output based models (Koks and Thissen 2016): (1) the consequences of production inefficiencies resulting from damaged industries aiming to operate at full capacity; and (2) the required increase in production in regions not affected by the direct impact to take over the production lost in the affected region (i.e. substitution). We use the MRIA model in combination with a multiregional subnational dataset for the European Union (Thissen et al. 2013, 2018). This dataset consists of multiregional supply-use tables and bilateral trade between 270 NUTS2 regions for the year 2013. A particular novelty of this approach is the high spatial resolution (NUTS2 administrative level) on a continental scale, considering not just transboundary effects between different countries, but also between regions in different countries. This allows us to capture specific trade flows that might be lost when not including interregional trade or when modeling on a country level.

Indirect flood losses simulated by MRIA are calculated based on the reduction in industrial production capacities due to the asset damages. MRIA subsequently calculates how trade flows from and to other regions change because of the flood, either positively or negatively. This trade flow change is the main driver of indirect economic effects in other regions. Negative effects occur as a result of reduced supply and demand in the affected industries of the flooded regions. Positive effects occur because industries (i.e. intermediate demand), governments and households (i.e. final demand) not directly affected by the flood seek to satisfy, within existing trade relations, their demand for products elsewhere. In their position, agents in the model attempt to find alternative possibilities to satisfy their demand based on existing trade relations. More specifically, we do not simulate the creation of new trade relations, which would require a more evolutionary economics approach (Boschma and Lambooy 1999) and would make the model dynamics much more complicated. This would substantially reduce the ease of interpretation of the outcomes. Finally, a cascade of effects may occur when the production capacity of industries in non-flooded regions is insufficient to completely take over production from a flooded region.

In line with standard input–output modeling, the MRIA model is based on the assumption of a demand-determined economy (Leontief 1951). In other words, the demand from all regions and from the rest of the world must be satisfied by the total supply in all separate regions and the rest of the world. The MRIA model is based on the region-specific technologies of industries used to make different products derived from regional technical coefficient matrices (Thissen et al. 2013, Koks and Thissen 2016). Hence, the technologies can be seen as the inputs, including capital and labor, required to produce an output of different products. Products are produced at the lowest costs, and together with the demand for products in every region, these costs determine which technologies are used as well as the extent of their use. In other words, industries in the model have cost-minimizing behavior. This may mean that inefficient technologies are being used to produce products when production with the ‘optimal’ technology is limited due to supply constraints. To avoid extremely inefficient production in the affected region by industries that produce this product only as a by-product, it is assumed that before a region reaches its maximum regional capacity it already begins importing goods from other regions, rather than attempting to produce these goods itself.
For a complete description of the model, please refer to Koks and Thissen (2016).

Ideally, modeling the macroeconomic impacts of disasters should include a temporal dimension. Unfortunately, empirical data on the dynamics of business recovery is scarce. To our knowledge, Thieken et al (2016) is the only European study providing some numbers on business recovery in Europe. As a result of the high uncertainty of the length and temporal shape of the recovery period, this paper considers three recovery curves (Koks et al 2016) and different recovery durations, depending on the reduction in gross value added (GVA) (figure S2). The mean recovery duration is based on the survey results of Thieken et al (2016). In the presentation of the results, we use the mean of the different recovery outcomes for each flood event and climate projection model. This way the possible impacts of climate change are more intuitive to interpret.

In addition to the commonly assessed output losses of a natural disaster, the MRIA model uniquely determines losses due to the use of inefficient production technologies. This second type of loss, which results from greater inefficiencies in the production process, increases production costs. The MRIA model also includes positive production effects in regions taking over production from affected regions (i.e. substitution effects). These positive effects that may occur are commonly observed in both macroeconomic modeling approaches (Bosello et al 2012, Willner et al 2018) and in post-disaster aftermaths (Leiter et al 2009, Abe and Ye 2013). Finally, the model outcome is loss estimation expressed in terms of expected annual output losses (EAOL). Through a combination of the outcomes of all floods in all the river basin districts, it is possible to determine the flood risk of each region in the EU, even when a region is not directly hit by a flood.

3. Results

The results are presented in terms of expected annual damages (EAD) for asset damages (i.e. damages to physical elements) and EAOL for indirect losses (i.e. macroeconomic losses due to changes in economic activity as a result of the disruption). Indirect losses are split up in first-order (i.e. impacts to industries in the flooded region) and second-order (i.e. impacts to industries outside the flooded region). Results show that flooding can have widespread economic effects across Europe. The mean EAD in the baseline situation (Methods) is ~€1.6 billion per year, increasing to almost ~€5.5 billion per year with 3° of global warming (figure 1(A)). For the EAOL, the baseline situation shows a mean risk of ~€0.3 billion a year, increasing to around ~€1.2 billion a year with 3° of global warming (figure 1(B)). The difference between the considered levels of global warming is less pronounced compared to the general increase between the baseline and the future. This can be explained twofold. Firstly, the relative short reference windows (Methods), making the occurrence of rare events a bit of ‘hit-and-miss’ within the different reference windows. Secondly, at a certain point in time the present protection levels are exceeded, resulting in a strong increase in flood damage (as observed in figures 1(A)–(D)). With further warming, the flood levels may further increase, but that increase will be less compared to no flooding (present) versus flooding (future).

We find a mean ratio of ~20% between the total EAOL and the total EAD (figure 1(F)), with an increase towards the future (up to 40%). On the other hand, the mean ratio of first-order EAOL versus the EAD (figure 1(G)) is ~50%, increasing to almost 80% from the year 2070. This large difference between total EAOL and first-order EAOL is driven by the second-order effects (figure 1(D)), which shows net negative losses (viz. benefits). In our modeling approach, we find that European industries not directly affected can find alternative suppliers and markets within their existing trade relations to partly offset the total losses (Methods). Results showing that total losses are lower compared to the first-order losses as a result of market adjustments are in line with results found in Oosterhoven and Tobben (2017) and Willner et al (2018), but contradict with, for instance, Dottori et al (2018). This indicates that including cross-border trade (either on a regional or country level) in the model could offset some of the negative impacts. This was for instance also observed after the Tohoku Earthquake, where the United States stock exchange went slightly up (Norio et al 2011). First-order EAOL, however, increase more (~240%) towards the future compared to net benefits observed in the second-order EAOL (~200%). This indicates that with the occurrence of more intense and widespread flood events due to warming it may become increasingly difficult to offset (some of) the losses. Finally, applying a Mann-Kendall test on the losses over time (figure 1(E)) shows significant and positive trends for the total EAD, EAOL and first-order EAOL and a significant negative trend for the second-order EAOL.

On a sectoral level (figure 2), we find that the largest economic impacts occur in the commercial sector (figure 2(D)), followed by the manufacturing sector (figure 2(C)). This correlates well with the relative size in GVA of each of these sectors in the European economy: ~53% and ~21% for respectively the commercial and the manufacturing sector. On the other hand, the public sector constitutes less than 1% of the total losses, while it makes up around ~20% of the European economy. Towards the future, the share of the commercial sector in the total losses increases to over 70% with 3° of global warming, causing the relative share of all other sectors to decrease. Zoomed in on the different sectors, we find the largest future increase of...
Figure 1. Overview of aggregated economic impacts. Panels (A)–(D) present the outcomes for the baseline and 1.5°, 2° and 3° of global warming for respectively EAD (A), total EAOL (B), first-order EAOL (C) and second-order EAOL (D). The red dotted line represents the mean and the lower and upper whiskers represent, respectively, the lowest 25% of the calculated risk and the highest 25% of the calculated risk for the different climate projection models. Panel (E) presents the ensemble mean of damage and losses over time, where panels (F)–(H) show the ratios for respectively EAOL versus EAD, first-order EAOL versus EAD and second-order EAOL versus first-order EAOL.

Figure 2. Future losses per sector. Panel (A) presents the annual mean and 10 year running mean for each sector. Panels (B)–(F) presents the EAOL for respectively agriculture, manufacturing, commercial, public utilities and public services for the baseline and 1.5°, 2° and 3° of global warming. The red dotted line represents the mean. The lower and upper whiskers represent, respectively, the lowest 25% of the calculated risk and the highest 25% of the calculated risk.
the (median) losses for the commercial sector (∼980%), followed by public utilities (∼530%). In our approach, public utilities are not directly disrupted (Methods). This means that this sector only endures losses through interdependencies with directly disrupted sectors. Public utilities are more dependent on demand from their ‘regular’ market and are less capable to find a substitution market somewhere else in case of reduced demand within its own region.

The results disaggregated to a country level show that the overall distribution of EAD is similar to the distribution of EAOL (figure 3), indicating that the first-order impacts and areas which are flooded in one of the simulated events (figure S3) are making up the biggest share of losses for a country. In absolute terms, the largest affected countries are Germany, Italy and France (figure S4), correlating with being the largest economies of Europe. When expressing EAD as percentage of GDP (figure 3(A)), we find that Bulgaria, Hungary and Latvia are the most affected countries, with damages up to 1% of the national GDP. For the EAOL, Hungary is still among the highest affected countries, but now followed by Czech Republic and Slovakia. Increasing losses with more degrees of global warming are particularly found in Germany, Austria, Italy and France. Some of the countries which are almost not affected by flooding in our simulations, such as The Netherlands and Denmark (figure S3), show (very) small net benefits. This indicates that countries not directly affected are, in our approach, capable to offset the negative effects elsewhere through market adjustments and substitution effects.

Effects can differ considerably between regions (figure 4). In order to clearly see such regional differences, we do not distinguish between baseline and the future scenarios, but pool the results over all flood events. When looking at the ratio between total EAOL and EAD on a regional level (figure 4(B)), we find that around 30% of the regions show a ratio higher than one, indicating that their indirect economic losses outweigh the asset damages. This can be caused by high economic activity in flood-prone areas, or by strong disturbances of a region’s economy by flood events in other regions. A spatial comparison of first- and second-order indirect losses (figure 4(C)) shows that most regions in Central and Western Europe are characterized by either both high first- and second-order EAOL or high second-order EAOL. This suggests that the traditional ‘economic heart’ of Europe is vulnerable to flood events both within its territory and in
regions with strong trade and production links via value chains. In many southern parts of Germany and The Netherlands, but also in other regions scattered across Europe, indirect impacts from trade disruptions with affected regions elsewhere are more substantial compared to local indirect effects. Most of France and Spain, and large parts of Italy, show both high first- and second-order EAOL, indicating they are particularly impacted to flooding. For the UK and Greece, we find relative low first- and second-order impacts for all flood events, primarily driven by the few flood events occurring in these countries in our event set.

On a sectoral level (figure 4(D)), regional patterns are somewhat different compared to the continental impacts (figure 2). We find that for ~48% of the regions, the manufacturing sectors are most heavily affected due to their production processes that often involve long value chains, making them vulnerable to disruptions. The second-most affected sector is commercial services (~28%). Yet, the commercial impacts on a pan-European scale are 140% higher compared to the losses to the manufacturing sector, indicating that when the commercial sector is the most affected sector, it is also more severely affected. This is due to the higher value added component in services. This conclusion can also be observed in figure 4(B), which shows both low first- and second-order EAOL in regions where manufacturing is the most affected.

Figure 4. Regional dynamics. Panel (A) shows the future increase in EAOL compared to the baseline. Panel (B) shows for each region the mean ratio between asset damages and the total indirect losses over all flood events. Panel (C) shows for each region the relative size of first-order and second-order economic effects. Low indicates the losses are below the European median. High indicates the losses are above the European median. Panel (D) shows for each regions which sector is the most impacted over all flood events.
This is exemplified in most regions of the United Kingdom, The Netherlands and Poland.

4. Discussion and conclusion

This is the first pan-European study to present, on a subnational level, how a flood can cause supra-regional effects and how this may change towards the future as a result of climate change. The results show that, overall, asset damages cause the highest impacts. However, there is a large spatial variation in the results, showing that some regions may suffer higher indirect impacts. Towards the future, we find that the ratio between EAOL and EAD is increasing, indicating that the indirect effects will become worse. This is primarily caused by an increased occurrence of larger flood events in the future, where it becomes more difficult to find substitutes for all lost products.

Modeled asset damages in this study are validated in the study of Alfiieri et al (2018), which shows that they are well in line with observed asset damages. More difficult is the validation of the modeled indirect losses (Koks 2018), which has proven to be difficult as the wider economic impacts after a disaster are not (well) documented (Dottori et al 2018) and, for Europe, are lacking almost completely. As such, it is important to interpret the results of this study as first estimates of what the potential impacts of large-scale flooding in Europe could be. Nonetheless, this study provides us with essential insights on the macro-economic dynamics of a post-disaster economy.

To validate the outcomes, we can compare the results and model behavior with similar academic exercises (Bosello et al 2012, Carrera et al 2015, Oosterhaven and Tobben 2017, Chen et al 2018, Willner et al 2018), but more research in this area is required. Our results show that some of the negative impacts can be offset by market adjustments through trade and substitution, resulting in lower indirect impacts compared to the direct impacts from asset damages. Multiple studies, applying different modeling frameworks capable of accounting for (some) flexibility in the economy, show similar results (Bosello et al 2012, Carrera et al 2015, Oosterhaven and Tobben 2017, Willner et al 2018), Bosello et al (2012), for instance, shows that countries which are not directly affected can have small benefits; a relative flexible market can ‘smooth’ an initial negative shock (Bosello et al 2012). This is similar to the effects we find in The Netherlands and Denmark. Additionally, previous studies have also shown that when the size of the disaster increases, positive market adjustments become less likely (Cunado and Ferreira 2014). This is similar to what the results in this study show with increasing levels of warming, when the magnitude of the floods tend to increase.

Our results contribute to the objectives of the Sendai Framework for Disaster Risk (Mysiak et al 2016), and the Warsaw Mechanism for Loss and Damages (Mechler and Schinko 2016), which explicitly state that a better understanding of disaster risk is important for post-disaster recovery and developing adaptation strategies. This study shows that by including indirect losses, risk assessments become more complete. As indirect losses account for a considerable share in overall impacts, risk management partnerships need to be broadened, introducing new types of adaptation measures to reduce (residual) risk. Examples are risk transfer schemes that stimulate quick recovery, targeting also sectors that lie outside the affected regions, but are economically connected to them. Other adaptation options include expanding inventory policies such as Europe’s Imports and secure supplies to different crucial products, for instance those used in the construction sector. A call for disaster risk reduction measures is clearly addressed in the aforementioned global policies. The approach developed in this study can support risk assessment and adaptation policies, indicating where bottlenecks can occur in the European economy in the aftermath of an extreme event, both now and in the future, and where to prioritize recovery funds.

Acknowledgements

The research leading to these results has received funding from the EU 7th Framework Programme through the project ENHANCE (Grant Agreement No. 308438) and the Netherlands Organisation for Scientific Research (NWO) VICI (453-13-006) grant programme.

ORCID iDs

E E Koks @ https://orcid.org/0000-0002-4953-4527
L Alfiieri @ https://orcid.org/0000-0002-3616-386X

References

Abe M and Ye L 2013 Building resilient supply chains against natural disasters: the cases of Japan and Thailand Glob. Bus. Rev. 14 567–86
Alfiieri L, Bisselink B, Dottori F, Naumann G, de Roo A, Salamon P, Wyser K and Feyen L 2017 Global projections of river flood risk in a warmer world Earth’s Future 5 171–82
Alfiieri L, Dottori F, Betts R, Salamon P and Feyen L 2018 Multi-model projections of river flood risk in Europe under global warming Climate 6 6
Alfiieri L, Feyen L, Dottori F and Bianchi A 2015 Ensemble flood risk assessment in Europe under high end climate scenarios Glob. Environ. Change 35 199–212
Boschma R A and Lambooy J G 1999 Evolutionary economics and economic geography J. Evol. Econ. 9 411–29
Bosello F, Nicholls R J, Richards J, Roson R and Tol R S J 2012 Economic impacts of climate change in Europe: sea-level rise Clim. Change 112 63–81
Carrera I, Standardi G, Bosello F and Mysiak J 2015 Assessing direct and indirect economic impacts of a flood event through the integration of spatial and computable general equilibrium modelling Environ. Model. Softw. 63 109–22
