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Advancing the economic and social perspectives of flood risk for disaster risk reduction and climate adaptation

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Abstract

Sound risk assessment is essential for developing effective disaster's risk reduction and climate change adaptation policies. This thesis investigates social vulnerability and the economic cost of flood risk, which are indeed two significant components of risk. The thesis provides a comprehensive analysis of risk in the Po river basin (Northern Italy), including social vulnerability. Moreover the thesis presents an innovative integrated impact assessment model for ex-ante and ex-post economic analysis of disasters. The model is applied to two case studies. The ex-post analysis re-examines the economic damage of the 2000 Po river flood, including the assessment of the wider economic losses, generally omitted in disaster's accountancy. The ex-ante analysis estimates the expected annual output losses under current and future climate in Italy at regional level, providing insights about the benefits of climate change adaptation. This document demonstrates that improved risk assessments are essential to mitigate risk and enhance adaptation.

Summary

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1. Introduction

1.1. Background: climate change and flood risk

1.1.1. Meteorological and climate extremes

The Working Group I (WGI) contribution to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2013a), and the IPCC's Special Report on extreme events (IPCC 2012) observed that the frequency and intensity of many climate and weather events have changed globally since 1950. The anthropogenic influence, though the emission of greenhouse gases (GHG), has likely affected the global water cycle since 1960, modifying precipitation patterns over land and increasing the intensity of heavy precipitation (IPCC 2013a). While the frequency and intensity of extreme precipitations display a great variability in location and time across the globe, it is likely that heavy precipitation events have increased also in Europe (IPCC 2013a). Climate models forecast that global mean surface temperatures (relative to 1986–2005) will likely increase in the ranges 0.3 - 1.7°C to 2.6 - 4.8°C depending from the concentration-driven CMIP5 model simulation (RCPs) (IPCC 2013a). In a warmer world, extreme precipitation events will very likely be more intense and more frequent over most of the mid-latitude land masses (IPCC 2013a). In Europe there will be a marked increase in extremes heavy precipitation events (Beniston et al 2007). The magnitude and confidence of the increase depend on the region. In the Northern and Central Europe there is high confidence of increase (IPCC 2014a). Future projections in Southern Europe are regionally and seasonally variable (IPCC 2012).

1.1.2. Flood economic losses: trends and projections

The water-related extremes, such as floods, account for the greatest share of global natural disasters' inflicted economic damage and death toll (Jonkman and Kelman 2005; Kunreuther and Michel-kerjan 2007; United Nations International Strategy for Disaster Reduction Secretariat 2009). Flood events can be very costly. For example the recent Central and Eastern European floods in 2013 caused a total loss of 15 billion Euro (in 2013 prices) (Munich Re 2014).

Europe is particularly prone to water related disasters. According to the NatCatService (MunichRE 2010), 80 percent of the economic losses caused by natural disasters that occurred during the period 1980-2009 were related to hydro-meteorological events (EEA 2010). Hydrological events only (i.e. flood and wet mass movements) account for 25 percent of the overall losses in the at that time 32 member States of the European Environmental Agency (EEA), estimated as 414 billion Euro over the period 1980-2009 (in 2009 values) (EEA 2010).

There is evidence that economic losses due to flooding have increased across the globe (Munich Re 2014; IPCC 2014b). In Europe in particular the increase of losses is well documented (IPCC 2014b). There is high confidence that increasing urbanization, exposure of persons and properties in risky area, and changing peak river discharges have contribute to increased economic losses and people affected over the last decades (IPCC 2014b). A number of studies have already assessed that growing population and capital density, unsustainable development, inappropriate land use threaten to intensify natural hazards' risk with even more concerning consequences in the future for the environment and societies (Plate 2002; Pottier et al 2005; Bouma et al 2005; Lehner et al 2006; Bočkarjova et al 2007; Wheater and Evans 2009; IPCC 2012; Jongman et al 2012b; Aerts et al 2013a; Hallegatte et al 2013; Jongman et al 2014).

Instead, climate change effects are less evident in flood losses trend. Barredo (2009) argues that, if flood losses are normalized to time-variant socio-economic factors (e.g. population, wealth, inflation), there is no detectable sign of human induced climate change effects in Europe (Barredo 2009). Barthlet and Neumayer (2011) analysis of normalized trends of insured losses show a positive trend of flood losses, but only in the United States over the period 1973-2008 (Barthel and Neumayer 2011). On the same line of Barredo (2009), Visser et al. (2014) results show that the exposure of people and economic activities are the main drivers of the increasing trend impacts of weather related disasters (Visser et al 2014). This suggests that climate change and increasing flood losses is not a straightforward relation, at least for the past.

Compared to the IPCC SREX report (IPCC 2012), the IPPC AR5 (IPCC 2014a) has now increased the level of confidence about the likelihood of change in the magnitude and frequency of heavy precipitation in Europe (from likely to very likely). Therefore climate change contribute to future losses might became more relevant (Bouwer et al 2010; Te Linde et al 2011; Feyen et al 2012; Rojas et al 2013). The EEA already warned that flood related losses will rise consistently in Europe (EEA 2012). Because of climate and socio-economic changes future losses might increase 17-fold by the end the century in Europe under the A1B emission scenario (Rojas et al 2012).

1.2. Measuring flood risk

1.2.1. Risk assessment frameworks

As already mentioned the modern approach towards natural disasters has shifted away from being hazard-oriented towards a risk-based approach (Alphen et al 2006; Lastoria et al 2006; Begum et al 2007). In the past decade, socio-economic components gained more importance as a result of a shift from the flood protection paradigm to the flood risk management approach (Meyer and Messner 2005).

The literature, over the years, proposed several risk assessment frameworks, each with advantages and limitations. A variety of definitions have been proposed to define *flood risk.* For example, in the FD, flood risk is defined as '*the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event*' (EC 2007). Instead, in the IPPC Special Report on Extreme Events (SREX), disaster risk is defined as '*the likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery'* (IPCC 2012). Moreover, the United Nations International Strategy for Disaster Risk Reduction (UNISDR) defines disaster risk as *'the potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period'* (UNISDR 2009).

The theoretical revision of the terminology of risk goes beyond the scope of this work, however, for a better understanding of the context, it is worth to examine the different approaches taken by two scientific 'communities': the climate change adaptation and the and disaster risk reduction. Until recently, the climate change scientific 'community' focused on the combination of hazardous physical events interacting with vulnerable conditions of the society, instead the disaster risk reduction 'community' stressed the combination of probability and potential consequences. These two perspectives of same need (the assessment of flood risk) lead to the diffusion of two main concepts to estimate flood risk, which are defined in equations (1) and (2):

(1) $R = f(H, E, V)$

(2) $R = f(p, D)$

where R is risk and, in equation (1) H hazard, E exposure, V vulnerability, in equation (2) p probability, D damage. Here, hazard is defined as the probability of occurrence within a specified period of time in a given area of a potentially damaging event; hence it implies considerations of frequency and magnitude of threatening events (Lastoria et al 2006). Exposure includes people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (UNISDR 2009). Vulnerability refers to a propensity or susceptibility to suffer a loss and it is associated to a range of physical, social, political, economic, cultural, and institutional characteristics. Damage refers to the impacts of an event and the associated losses, which can be categorized into direct and indirect impacts, both of them further divided into tangible and intangible (NRS 1999; Merz et al

2010b; Balbi et al 2011). Direct impacts are the losses affecting humans, assets, property and any other objects in the areas that had physical contact with the flood (Merz et al 2010b), and the market-based negative economic impacts are considered direct losses or asset losses (NRS 1999; Hallegatte 2014a). Indirect impacts as those impacts induced by the event outside (and inside) the flooded area (Merz et al 2010b; Przyluski and Hallegatte 2011; Meyer et al 2013). Tangible losses can be measured in monetary terms (Smith and Ward 1998), while intangible impacts are difficult to translate into monetary values. Some examples of direct intangible impacts are loss of life, injuries, damage to cultural heritage, psychological distress (Merz et al 2010b; Meyer et al 2013). Indirect intangible impacts include trauma, loss of trust in authorities, and loss of jobs (Merz et al 2010b; Meyer et al 2013).

Equations (1) and (2) have been implemented, with case-by-case modifications, in most of the existing risk-related conceptual frameworks. Here below is a short summary of the most common risk frameworks, in chronological order:

a) Davidson (1997) risk assessment framework combines hazard (defined by the combination of probability and severity) exposure (including structures, population and the economy) vulnerability (defined by physical, social, economic and environmental factors) and capacity and measures (which includes physical planning, social capacity, economic capacity and management) (Davidson and Shah 1997);

b) Cutter (1996), then updated with (Cutter and Morath; Cutter et al 2008; Cutter et al 2010), created the *hazard of place model of vulnerability*, with the aim to facilitate the evaluation of single or multi-hazard contexts with different geographical and socio-spatial characteristics. The framework includes the social and biophysical vulnerabilities, which became critical component of the risk management cycle (Cutter 1996);

c) Crichton (1999) framed the '*risk triangle*' as a function of hazard, exposure and vulnerability, where hazard and exposure are probabilistic and vulnerability is defined as tangible direct losses (in monetary terms) (Crichton 1999). The '*risk triangle*' has been lately elaborated further and expanded in the EU KULTURisk Project (Balbi et al 2011);

d) Villagran de Leon (2001) modified the 'risk triangle' replacing exposure with *deficiencies in preparedness* (Villagrán De León 2001), later updated in (Villagrán de León 2006). Villagran de Leon's work gave great emphasis to risk mitigation measures;

e) Turner (2003) provided for the first time a multi-dimensional framework based on three levels of analysis: the place, the region and the world. Exposure, vulnerability and resilience interact with the drivers of risk, which are the variability and change of environmental and human conditions, and the consequences, which include adaptation and impact responses (Turner et al 2003);

e) More recently, Birkmann (2006) consolidated the holistic approach firstly developed by Cardona (2001) and Bogardi and Birkmann (2004) (Cardona 2001; Bogardi and Birkmann 2004; Birkmann 2006a). As in Cutter (1996) the risk assessment framework is recursive. Disaster risk reduction is described in a cyclic process. Vulnerability is determined as the intersection of exposed and vulnerable elements with coping capacities. Risk and vulnerability are divided in three main spheres: environmental, social and economic. Risk reduction is provided by emergency management and preparedness, which influence vulnerability and hazard (through land management). The consequent level of risk provide feedback to risk reduction in a recursive and circular mechanism;

f) The increase of 'complexity' introduced by Birkmann (2006) was then reinforced in the MOVE framework (Birkmann and von Teichman 2010), which included the risk management component. Vulnerability, which is a combination of susceptibility and fragility, exposure and lack of resilience, are defined at different scales: local, subnational, international (as in Turner (2003). Risk which is characterised by the output of three dimensions: economic, social and environmental. The level of risk, its governance and risk management are part of a recursive cycle;

g) A slightly different approach is taken by Klein (2004) in the IPPC Assessment Report 4 (IPCC 2007). In his framework great influence is given to the social aspects influencing vulnerability. Vulnerability is a function of exposure, sensitivity and adaptive capacity. Adaptation responses increase or decrease the level of vulnerability. This framework does not directly mention risk, focussing mostly on vulnerability;

e) Concluding, the IPPC SREX report (2012) proposed an approach that finally combines the climate change and disaster risk reduction approaches. Disaster risk is a combination of vulnerability, exposure and weather and climate events. Development and climate interfere with the 3 dimensions of risk through risk management and adaptation on one side and natural variability and climate change on the other side (IPCC 2012).

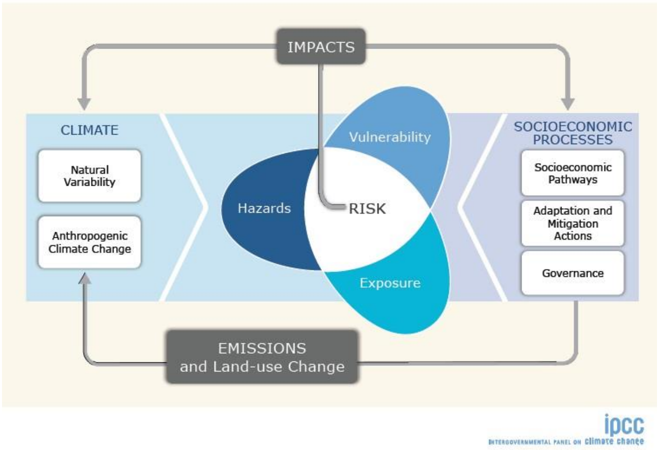

Figure 1: IPPC SREX report (IPCC 2012) risk assessment framework.

Despite evidence of integration between the climate change (CC) and disaster risk reduction (DRR) ‘communities’, there is still reason to believe that some division remain between the two remains. Perhaps the most evident difference is that disaster risk reduction scholars still insufficiently deal with the social aspect of risk, while climate change scholars continue to insufficiently deal with the pragmatism of probabilities and costs. Each approach has advantages and limitations. The DRR ‘engineering’ approach provides easily digestible maps and rankings for policy making, while the CC ‘social’ approach results are more difficult to operationalize, particularly in policy making processes. However the ‘social’ approach provides precious insights about the processes, the feedback and the interactions of the different components of risk. The ‘engineering’ approach is frequently static, focussing solely on the impacts disregarding causes and secondary effects. Given the evidence of increasing influence of climate change on extremes, the integration of the two ‘communities’ could foster better adaptation in the context of risk management (Jones and Preston 2011).

Concluding, in this thesis, I have tried to consider and implement both approaches. Section 2 estimate risk based on equation (1), while Section 4 considers equation (2). The risk assessment framework I refer is principally the one provided by the IPPC SREX report (2012).

1.2.2. Measuring the economic cost of flood risk

As already mentioned, in the last decades flood losses has increased consistently (Munich Re 2014). Although there is disagreement about the role climate change played in the uprising trend of the disaster losses, it is evident that exposure has increased, leading to additional impacts (IPCC 2014b). However, there is still little understanding of the real economic cost of flood risk. In general only direct tangible losses are considered (De Groeve et al 2013), to the detriment of other losses such as business interruption, indirect impact, wider losses, micro and macroeconomic impacts, i.e. the damage to the economic flow, the so called output losses (Hallegatte 2014a). For example, typically estimates from the European Environmental Agency (EEA) (EEA 2012) and global disaster databases such as EM-DAT (Centre for Research on the Epidemiology of Disasters – CRED), NatCatSERVICE (Munich Reinsurance Company) and Sigma (Swiss Reinsurance Company) account for direct impacts only, with partial or incomplete consideration given to wider economic effects.

Most flood impact assessments focus on direct tangible impacts, i.e. the damage to the stock of capital. This is due to the fact that direct tangible losses are the most evident and, relatively speaking, the more 'evident' to assess. The most common methodology used in literature to assess flood risk is through the use of flood depth-damage functions (Thieken et al 2008; Kreibich et al 2010; Feyen et al 2012; Rojas et al 2013; Balica et al 2013; Aerts et al 2013b; De Moel et al 2014; Saint-Geours et al 2014). Risk mapping of direct damage provides useful information for: a) identification of priority areas , b) insurances and financial risk management, c) cost-benefit analysis of risk management measures, d) elaboration of exceedance probability-loss curves and calculation of the Expected Annual Damage (Meyer et al 2009), which is often considered an indicator of flood risk (Feyen et al 2012; Rojas et al 2012; Aerts et al 2013b; De Moel et al 2014).

Over the past few years an increasing number of studies highlighted the importance of assessing the economic flows which are diverted or interrupted by a natural hazard (Cochrane 2004; Rose 2004; Messner et al 2007; Okuyama 2007; Green et al 2011; Przyluski and Hallegatte 2011). Different methodologies have been proposed: post event economic surveys (Kroll et al 1991; Pfurtscheller 2014; Molinari et al 2014), econometric models (Albala-Bertrand 1993; Noy and Nualsri 2007; Strobl 2010; Cavallo et al 2012), input-output (I-O) models (Okuyama et al 2004; Hallegatte 2008; Hallegatte et al 2011; Ranger et al 2011; Henriet et al 2012; Okuyama 2014), computable general equilibrium (CGE) models (Rose et al 1997; Rose and Liao 2005; Bosello et al 2006; Tsuchiya et al 2007; Berrittella et al 2007; Jonkhoff 2009; Pauw, K. et al 2011; Bosello et al 2012; Haddad and Teixeira 2013).

However, wider losses scarcely considered. Against this background, this thesis provides an ex-post (Section 3) and ex-ante (Section 4) economic impact assessment for disaster's accountancy.

1.3. The scope and goal of this thesis

The modern flood risk management approach acknowledges that floods cannot be stopped from occurring and places emphasis on how to reduce hardship and impacts to risk-prone communities. This shift is also supported by the European Union Directive on the assessment and management of flood risks (FD, 2007/EC/60) and the EU Adaptation Strategy (EC 2013). The FD recognizes that flood management plans need to consider the harmful potential risk of floods, and identify tangible measures able to reduce exposure and sensitivity to floods, and improve risk governance.

Better risk assessment may help in designing risk mitigation policies which are more efficient and less expensive. The shift from the *protection* to the *preventive* approach to requires the availability of reliable information about vulnerabilities and potential losses. The improvement of social vulnerability understating is therefore essential to better shape risk reduction policies, both at European, national and local level. Particularly at river basin district level, the inclusion of vulnerability indicators in flood risk mapping complies with the requirements of the FD and it benefits to the improvement of risk distribution over the territory.

Moreover, there is an increasing need for the construction of a reliable, and comparable, flood losses database (De Groeve et al 2013). Existing databases undervalue the full cost of disasters to societies and environment because most of the time they account for direct impacts only, with partial or incomplete consideration given to indirect, wider and macroeconomic effects. Consequently economic outcomes of natural hazards are poorly understood and losses might be over or under estimated. This may leads also to a misleading distribution of flood risk over the territory. For example, an area which is not directly prone to flood hazard could also suffer large indirect losses, because of interconnectivity and ripple effects. This is rarely accounted in flood risk assessments nor considered in flood losses accountancy or risk mapping. If only direct losses are accounted for, policy responses may be misguided to restore (in the aftermath of a disaster) or protect (before the disaster) the assets at risk only, instead of building a resilient society and economic system. In times of financial constrain, public spending in risk mitigation policies shall be efficient and effective in developing resilience and reducing vulnerability. Given the increasing contribution of the private sector (e.g. insurances) in the restoration of capital assets, the estimation of this type of losses might not be the real economic cost of flood risk to the society.

Therefore, this thesis aims to investigate the socio-economic factors which influence flood risk (Section 2), suggesting their inclusion in the flood risk mapping developed by local river basin authorities, as required by the 2007/60/EC Flood Directive. Social vulnerability is analyzed through the hazard of place model of vulnerability (Cutter 1996). Moreover, the macroeconomic outcome of disasters is considered in two analysis, through an ex-post (Section 3) and ex-ante (Section 4) impact assessment. Given the lack of knowledge in the wider economic effects of flood risk, greater emphasis is given to indirect impacts, i.e. output losses.

These objective are addressed in three Sections, which have been developed as peer-reviewed papers:

1) In Section 2 I present a research on social vulnerability to flooding, and its inclusion in a flood risk assessment. Vulnerability is estimated through the hazard of place model (Cutter 1996), focusing on the social component of vulnerability. The aim is to support the elaboration of

Riven Basin Districts' Flood Management Plans, currently under development by several river basin Authorities throughout Europe within the 2007/60/EC Flood Directive. The Directive does not constrain river basin Authorities to a specific methodology, but it requires the inclusion of social characteristics for the estimation of risk. The case study of this work is the Po river basin, in Northern Italy. The study has been presented to the Po River Basin Authority for further implementation and consideration in the elaboration of the flood risk mapping required by the 2007/60/EC.

2) Following the importance of assessing wider economic losses described in this introduction, Section 3 elaborates an integrated methodology for assessing direct and indirect economic impacts of flooding. The methodology combines a spatial analysis of the damage to the physical stock with a general economic equilibrium approach using a regionally-calibrated version of a global Computable General Equilibrium (CGE) global model. The model is applied ex-post to the 2000 Po river flood in Northern Italy and the results focus on indirect impacts. To account for the uncertainty in the dynamic of economies in the aftermath of a disaster, three disruption and two recovery scenarios are considered. The assessment shows that wider impact, in particular, are essential for a full understanding of the economic outcomes of natural disasters.

3) Section 4 is an ex-ante assessment of flood risk in Italy. The methodology developed in Section 3 is further elaborated to estimate current and future flood risk in Italy, through the calculation of the expected annual output loss (EAOL). The economic effects are estimated per region, in terms of Gross Regional Product change and production loss from the 1980s till the 2080s. Climate change effects are based on 12 climate experiments under the SRES-A1B emission scenario. The simulations are made for two adaptation scenario. In this paper I argue that output losses, which represents the damage to the economic flows, that is the wider effects of a disaster to the economy, have significant policy relevance which shall not be neglected further in disaster's accountancy.

The geographical target of this thesis is on Italy, with a particular focus on the Po river basin. This basin is by far the largest and the most important of the country, both in social and economic terms. It ordinarily suffers from the impacts of flooding from its main river, the Po, and some of its tributaries, particularly those from the Alps. Moreover the human settlements and activities in the plain are highly dependent from flood protection measures.

Italy is extremely prone to flood risk, and more in general to hydrogeological risk. According to the national Institute for Environmental Protection and Research (ISPRA), the empirical records over the last decades show an average annual asset loss of around 1 billion Euro/year (ISPRA 2010). From

1900 (with sporadic data from 1500) the National Research Council’s AVI (Damaged Urban Areas) archive recorded 10,159 hydrological-related fatalities and over 4,566 events. In such a vulnerable environment further scientific evidence and innovative methodologies for risk assessment are beneficial the shaping of future climate change adaptation and risk mitigation policies.

2. Risk assessment to extreme hydrometeorological events: evidence from the Po River basin, Italy

Note from the author: The research presented in this Section has been published as an article in a book.

L. Carrera, F. Farinosi, and A. Maziotis, "Risk assessment to extreme hydrometeorological events: evidence from the Po River basin, Italy," in Social vulnerability to resilience: measuring progress toward disaster risk reduction, S. Cutter and C. Corendea, Eds. Bonn (Germany): SOURCE "Studies of the University: Research, Counsel, Education" Publication Series of UNU-EHS No. 17/2012. United Nations University Institute for Environment and Human Security (UNU-EHS), 2013, pp. 64–75.

Abstract: European River Basin District Authorities are in the process of implementing the 2000/60/EC European Water Framework Directive (WFD) and the 2007/60/EC Flood Risk Management Directive for extreme hydrometeorological events. The latter Directive requires Member States to produce flood risk maps by 2013 and flood risk management plans by 2015. In the midst of such dynamic context of European water governance, it is crucial for European River Basin District Authorities to develop a flood related risk assessment methodology. This study draws on an empirical analysis of an Italian case study, the Po River basin. Hazard exposure and social vulnerability are deduced from available information on hydrological risk, and socio-demographic data. Through the aggregation of these criteria this study frames a prototype risk assessment methodology for hydrometeorologic extremes, which includes social vulnerability. The framework is aimed to support River Basin District Authorities in the development of flood risk maps, and in the consequent monitoring of progresses in risk reduction.

2.1. Introduction

Climate conditions determine the natural variability of precipitations and water resources availability through time and space around the globe. In a climate change context, the "stability" of past climate cannot be taken for granted and the future is more and more uncertain. While the impact of increasing variability of climate is still unclear, there is evidence that societal exposure to hydrometeorologic extremes is growing (IPCC 2012). Global change, growing world population, unsustainable development, and inappropriate land use threaten to induce or intensify natural hazards' exposure with disastrous consequences for the environment and societies (IPCC 2012).

Extreme water-related hazards, like floods and wet mass movements, could be induced by several events, such as high tide, storm surge, overflow or breaks of embankments, dam failure, and extreme precipitation. Globally, water-related extremes account for the greatest share of natural disasters' inflicted economic damage and death toll (Kunreuther and Michel-kerjan 2007).

The modern flood risk management approach acknowledges that floods cannot be stopped from occurring and places emphasis on how to reduce hardship and vulnerability of risk-prone communities. This shift is also supported by the European Union Flood Risk Management Directive (2007/EC/60). The Directive states that flood management plans need to consider the harmful potential of floods and identify tangible measures able to reduce exposure and sensitivity to floods, and improve risk governance. In light of this, this paper analyses the importance of improved understanding of vulnerability to flood events. Specifically, the paper aims to define a flood risk assessment methodology, where vulnerability is investigated and combined with hazards and exposure. This methodology could support the elaboration of the regional flood management plans, currently under development by several river basin Authorities throughout Europe. The EC Directive does not provide a specific methodology, but it requires the inclusion of social characteristics for the estimation of risk. The methodology proposed by this paper is applied to a specific case study, the Po river basin, in Northern Italy, which ordinarily suffers from the impacts of flooding from its main river, the Po, and some of its tributaries, particularly those from the Alps.

To the authors' knowledge, vulnerability has never been included in the overall estimation of risk at the Po River basin. Therefore the importance of this study is the inclusion of social vulnerability as a fundamental factor for the definition of risk, at the same level as hazard and exposure.

2.2. Background

2.2.1. Legislative framework in Europe and Italy

On 23 October 2007, the European Commission adopted the Flood Directive 2007/60/EC, which addresses the assessment and management of flood risks focusing on prevention, protection and preparedness (Table 1). The aim of the implementation of flood risk management plans is on the maintenance and/or restoration of floodplains, as well as measures to prevent and reduce damage to human health, the environment, cultural heritage and economic activity (EC, 2007). Member States therefore need to assess river basins, coastal areas that are at risk of flooding and the potential impact of floods in human life and economic activities. In order to be implemented, the European Flood Directive 2007/60/EC was subsequently introduced into the Italian Legislation through the Legislative Decree nr.49/2010 adopted on 23 February 2010. Since then, Italian river basin district Authorities, including the Po River basin District Authority, began the investigation of the vulnerability level of the territory to floods.

Table 1: Elements in the European Flood Directive 2007/60/EC and Italian L.D. 49/2010

Level	Description of activities
European	• Flood risk maps and hazards maps by 2013, considering three scenarios with rare (500 year return period), frequent (100-200 years return period), and common (20-50 years return period), including flood extent, water depths, flow velocity, number of inhabitants, and type of economic activities at risk • Flood risk management plan by 2015
National	• The Italian Legislative Decree 49/2010 requires that flood impacts shall be estimated using the following criteria: number of inhabitants, infrastructures and strategic structures (e.g., highways, railways, hospitals, schools, etc.), heritage and historical goods, distribution and category of economic activities, potentially polluting industrial plants and natural protected areas. Risk is defined as a conjunction of the probability of the event and potential impacts on human health, territory, environment, goods, cultural heritage and socio-economic activities

2.2.2. Conceptual background and experiences in measuring risk and vulnerability

The modern approach towards natural disasters has shifted away from being hazard-oriented towards a risk-based approach (Lastoria et al 2006). Until recently, research and protection to natural hazards policy had been dominated by a technical world view, focusing on the technical and financial aspects and ignoring the impact and significance of socio-economic drivers. However, in the past decade, social and socio-economic components gained more importance as a result of a shift from flood protection to flood risk analysis (Meyer and Messner 2005).

Three factors are defined as of great importance to set the framework of risk analysis: exposure, vulnerability and hazard. According to UNIDSR (2009) the risk to natural hazards is defined as the anticipated probability of harmful consequences or losses resulting from interactions between natural or anthropogenic hazards and vulnerable conditions with (human) exposure. The concept of risk can be represented with equation (1).

(1) $R = f(H, E, V)$

Where R denotes risk as a function of Hazard H, Exposure E and Vulnerability V.

Hazard is the probability of occurrence within a specified period of time in a given area of a potentially damaging event; hence it implies considerations of frequency and magnitude of threatening events (Lastoria et al 2006). Exposure includes people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (UNIDSR, 2009). Vulnerability refers to a propensity or susceptibility to suffer a loss and it is associated to a range of physical, social, political, economic, cultural, and institutional characteristics. For example, poorly built housing, schools, hospitals and lifeline infrastructure are characteristics of physical vulnerability (UNIDSR, 2009).

Kienberger (2012) states that vulnerability is present everywhere at any time, but its significance depends on its degree (Kienberger 2012): in certain areas it may be close to zero, while in others it may have a higher degree. A comprehensive overview of the evolution of approaches to vulnerability is provided by Cutter (1996) and Adger et al (2004). The authors state that much of the research in the past was concerned with identifying and predicting vulnerable groups and critical regions to hazards, whereas later applications focused on combining social, physical and ecological system vulnerability to future risks. Given the wide range of approaches to vulnerability, Adger (2006) concluded that a generalised measure of vulnerability is needed, defined as social vulnerability, which should account for the human well-being, the temporal dynamic dimensions of risk (e.g. mobility of income) and the distribution of vulnerability within the system (e.g. urban versus rural environments).

There have been several studies in the past that measured, qualified and/or assessed social vulnerability using both qualitative and quantitative techniques (Cutter 1996; Adger et al 2004; Birkmann 2006b). A qualitative vulnerability assessment takes into account the participation of individuals (Blaikie et al 2004; Moser 2011), whereas quantitative vulnerability assessments commonly include the selection of indicators obtained by a combination of norms (Vincent 2004; Adger 2006; Birkmann 2006b). Moreover, mixed assessment is possible; these represent a combination or association of qualitative and quantitative research elements in tandem which goes beyond simply collecting and analysing both kinds of data (Jean-Baptiste et al 2011; Creswell 2013). Kuhlicke et al (2011) provides a comprehensive overview of the strengths and weaknesses of the vulnerability assessments. However, many of the studies often lack a systematic and transparent approach (Birkmann, 2006). For example, there is still no consistent set of metrics used to assess vulnerability to environmental hazards, although there have been calls for just such an index (Cutter et al 2003). Research findings are fragmentary and there is still no consensus on (a) the methodology to assess social vulnerability, or (b) an equation that incorporates quantitative estimates of social vulnerability into either overall vulnerability assessment or risk (Kuhlicke et al 2011; Fekete 2012; Yoon 2012).

Therefore, it appears that defining and integrating the different dimensions of vulnerability for a comprehensive assessment of risk is far from simplistic. This paper will follow the approach developed initially through the Hazards of Place (HOP) model of vulnerability (Cutter, 1996). The HOP model shows how risk and mitigation interact in order to produce hazard potential, which is filtered through (1) social fabric to create social vulnerability and (2) geographic context to produce biophysical vulnerability (Cutter and Morath). In the HOP, a geographical information system was employed to set up areas of vulnerability based on twelve environmental factors such as flood plains, surge inundation zones, seismic zones and historical hazard frequency. Social vulnerability was defined based on eight socio-economic indicators such as total population and structure, differential access to resources/greater susceptibility to hazards due to physical weakness, wealth or poverty, level of physical or structural vulnerability (Cutter et al 2000). More recent studies from Cutter et al (2003) developed the Social Vulnerability Index (SoVI), which is based on 250 socio-economic and environmental variables that vary according to the context where the index is applied, and it defines a comparative assessment of the relative levels of vulnerability between places (Cutter and Morath).

2.3. Italian experiences in measuring vulnerability

A recent study by De Marchi et al (2007) assessed the risk of destruction and social vulnerability in an Italian Alpine region which was damaged by flash floods and debris flows between the 2000 and 2002. Although the area is partially outside the Po River basin, it remains a useful source of information for this study. The purpose of De Marchi's work was to promote preparedness, increase resilience, and reduce vulnerability at community level. Therefore the authors explored the main strengths and weaknesses of communities exposed to flood risk, focusing on socio-psychological, cultural, economic and organizational aspects. The main conclusions from that case study can be summarized as follows. Increase in risk awareness such as knowledge of hydro-geological risks and their unpredictability, frequency of the events and their consequences, and information about the role of protection works were considered of great importance for reducing vulnerability to floods. The efficiency risk management agencies can encourage people to enact self-protection behaviours. Risk maps need to be constantly updated to provide with valuable information regarding the risk-prone flooded areas. Finally, the designation of an area as a risky one might lead to a decrease in property values and as a result, residents who lived there are deprived twice, they do live in an unsafe area and it is not feasible for them to sell their property. Although this vulnerability assessment is not place-based, it is an Italian experience, which clearly defines amplification and attenuation factors of vulnerability at local level.

Other studies in Italy have also measured the risk and socio-economic impact of floods without assessing social vulnerability. Rusmini (2009) employed simulated techniques to assess and improve the accuracy in calculating the water extent and depth in flood areas in the Po River basin. A flood damage assessment and lives loss estimation were also conducted. Lastoria et al (2006) reported economic losses for the flood events that occurred in the country during the years 1951-2003, calculated based on the partial or total destruction of buildings, infrastructures and engineering works, interruption of economic activities and public services. Guzzetti and Tonelli (2004) underlined that in Italy, 382 municipalities (5.9 per cent) have a 0.90 or larger probability of experiencing at least one damaging flood or landslide, and 1319 municipalities have a 0.50 or larger probability of experiencing at least one flood or landslide for a 10 years period. Finally, the Po River Basin Authority in the Po River Basin Hydrology Management Plan (PAI) provides a comprehensive and elaborated risk assessment, including potential losses for dike failures, but it does not take into consideration recent vulnerability assessment frameworks (Po River Basin Authority, 1999 and 2002).

2.4. Area of study

2.4.1. Po River basin

With 71,000 km^2 (~24 per cent of the state territory), the Po River basin is the largest (single river) basin in Italy and the economically most important area (Figure 2). The basin area is home to 17 million inhabitants (~28 per cent of the state population). More than one third of country's industries producing 40 per cent of the national GDP are located in the basin area. The agricultural output accounts for 35 per cent of the national production. The agricultural sector generates an added value of about 7.7 billion €/year (~1.2 per cent of the total added value produced in the basin). The one thousand or so hydroelectric plants installed on the Po River and its tributaries generate on average 20 billion kWh/year (~48 per cent of the installed hydropower in Italy). Additional 400 thermoelectric plants generate around 76 TWh every year. The natural and artificial lakes in the basin regulate a volume of 1,858 million m^3 per year (Po River Basin Authority, 2006).

The river basin spreads over eight (out of twenty) Italian regions including Valle d'Aosta, Piedmont, Lombardy (all three entirely included in the basin area), Emilia Romagna (with about a half of the area included in the basin), Autonomous province of Trento, Veneto, Liguria and Toscana (marginally included in the basin area).

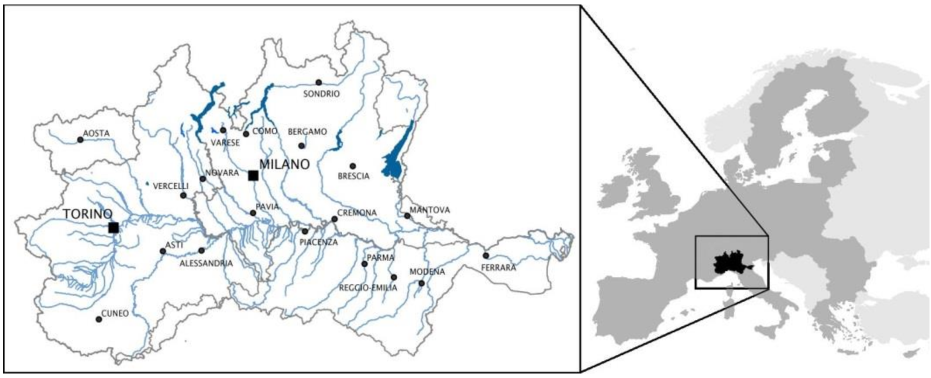

Figure 2 - Po River Basin and its surface hydrology.

The Po River basin annual average precipitation is 1,108 mm with maximum values in the Alps (over 2,000 mm per year) and minimum values in the eastern Paduan plain, (700 mm per year) (Po River Basin Authority, 2006). This amount of precipitation produces an annual water flow of 78 billion m^3, which correspond to a water flow of 2,464 m^3/s. Two third of this flow runs on the surface, that is approximately 47 billion m^3 per year, 1,470 m^3/s. The remaining 31 billion m^3 are consumed by evapotraspiration and deep percolation. Two mountain chains, Alps and Apennines, feed all rivers in the basin. River cycle characteristic depends on the source of water. Alpine rivers have water flow peak in summer due to ice melting, while Apennines' rivers have lowest peak in summer due to their dependency from precipitations, and highest peaks in spring and autumn.

The Po River basin is water rich thus its surface water component is remarkable. The principal reticulum includes 141 major water affluents (>20km of length), while the secondary surface river network is nine times more extended than the primary river network, which lengthens in the basin for over 6,750 km (Po River Basin Authority, 2006). Artificial networks, including irrigation channels and drainages, are also highly developed throughout the basin. This complex and extended water network is the result of thousands of years of human alterations of the natural environment. Flow of water from mountain basins and natural lakes to the Po River running along the Paduan Plain is intensively interfered by artificial abstractions, rice field submersions, dripping irrigation, deviations for irrigation channels, irrigation losses, and the interaction between surface water with aquifers. The surface water network also includes major artificial irrigation canals. Among them the Cavour Canal, the Emiliano-Romagnolo Canal (CER) and the Muzza Canal are of the most important in terms of water flow derived from the natural network.

Due to its long history of human development, Po River flooding events have been recorded since the year 204 BC, when Tito Livio reported a flooding event. Since then several major floods have been recorded. Over the centuries the river flooded several areas of the plain, including major cities and town, such as Rovigo, Mantova, Ferrara, Modena, Cremona, and Piacenza. The most destructive flood recorded in the recent period occurred in the year 1951, when 100,000 hectares of Polesine area (Rovigo) were flooded. It caused 84 causalities and displaced 180,000 people.

Nowadays the Po River basin is extremely anthropized. Natural river flow is regulated by hydrogeological protection structures, which contain the flow within the riverbed and reduce the ability for extreme events to impact its natural flow. Until the end of nineteenth century, the dyke protection system along the Po River Basin was not fully closed, and rivers flooded into the plains during extreme precipitation events. At present the dyke protection system along the Po riverside is completed, with an extension of 2,292 km (Po River Basin Authority, 2006). Floods are ordinarily contained within the second level dykes, so that the surrounding plain is rarely inundated. In order to control Po River flow back effects on river tributaries, both continuous and discontinuous dykes were also constructed in the lower river courses of Po tributaries. Continuous dyke systems have also been constructed in all rivers of Emilia and lower parts of Mincio, Oglio and Adda. Smaller protection dykes exist in lower parts of Piedmont plain rivers (Sesia and Tanaro). Some river beds have very high level of confinement along their course, among them we find: Adda, Serio, Oglio, Mella, Chiese, Toce, Dora Baltea, Dora Riparia, Bormida, Orba. Rivers in the plain have frequently higher level of anthropization than the ones in the mountains. Because of urban pressure, riverbeds are normally channelized when running in the plains. This fact increased the inability of the water network to adapt to changes in water flow, which consequently increases the vulnerability of the system to extreme events. Within the basin it is extremely rare to find rivers characterized by untouched natural conditions and limited artificial regulation.

2.4.2. Hydrological profile

The Po River Basin Authority within the Hydrological Management Plan (PAI) provides a dataset of potential hazards related to the hydrological risk. PAI analyses the hydrological risks (Po River Basin Authority, 1999), territorial hydrological characteristics and system of interventions. In order to improve the basin's security level against hydrological risk, the plan defines structural (hydraulic works) and non-structural (rules) actions for soil and water uses. The PAI aims to design a functioning framework of the basin with the clear objective of preventing the risk, therefore it:

- defines and quantifies critical exposure, actual and potential, investigating relevant causes;
- identifies required actions to deal with specific issues related to the gravity and extent of damages;
- formulates safeguards rules that enable the effective and positive actions to protect soil and water.

The PAI considers two types of areas: territories where emergency status has been declared and those characterised by high level of risk for people, goods infrastructure, cultural and environmental heritage security. The plan identifies potential hydrological risk for flood-prone areas, with three grade of inundation gravity (very high risk, high risk, medium risk), including also river buffer areas prone to rare flood risk (500 years return period), frequent flood risk (100-200 years return period) and common flood risk (20-50 years return period). The Plan also provides geo-referenced information about active, stable, and stabilized landslides. Figure 3 represents the exposed areas to hydrological risk in the Po River basin.

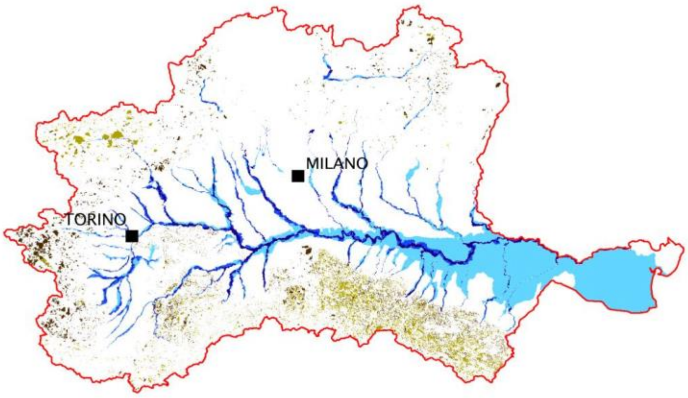

Figure 3: Hydrological Management Plan, flood and landslide prone areas of the Po river basin. Blue: flood and inundating prone areas. Brown: landslide prone areas. Source: own elaboration based on the Po River Basin Authority dataset.

2.5. Methods and data

2.5.1. Hazard profile of the basin

In order to define the hazard profile of the basin (Figure 4) the PAI described above has been analysed for combining the different typologies of hazard (landslides, floods, inundation) threatening the basin, in order to obtain a hazard value at municipality level. Municipalities are divided into four categories: low, medium, high, and very high hazard. The most hazardous areas appear to be the mountainous regions of the basin. This could be explained by the large presence of small rivers and torrents that, in case of extreme rainfall events, are suddenly subject to flash floods with catastrophic consequences. Moreover, the mountainous regions of the basin are characterised by the presence of multiple active or stabilised landslides that constitute a serious problem in case of a consistent increase of the humidity rate of the soil. It could appear controversial that the alluvial plain created in the geological eras by the main river of the basin is characterised by a low hazard only. This is mainly due to the fact that several engineering and infrastructural interventions (dykes, embankments, levees, artificial channels, etc.) have been implemented in the last three centuries to contain floods with a return period lower than 500 years.

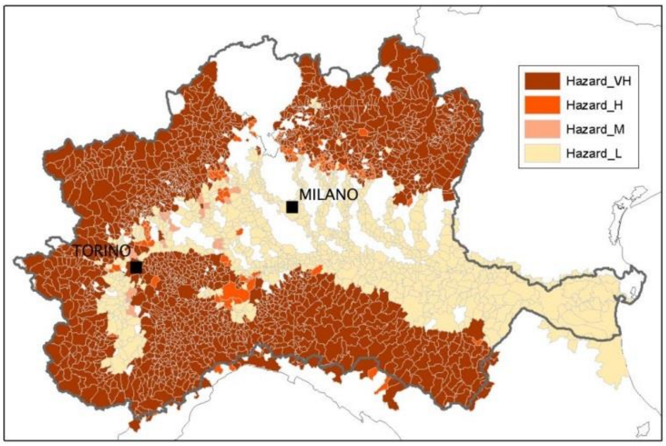

Figure 4: Hazard map of the municipalities in the Po river basin. Source: Authors' own elaboration based on Po River Basin Authority data. The map presents 4 classes of hazard: low, medium, high and very high.

2.5.2. Exposure profile of the basin

In order to define the exposure profile of the basin, the percentage of the constructed area over the total area of the municipality, from Corine Land Cover (CLC) (EEA 2006), has been chosen as a proxy of the value exposed to the hazard. The final exposure map classifies the municipalities into five categories: 0 to 2 per cent, 3 to 5 per cent, 6 to 10 per cent, 11 to 20 per cent, 21 to 100 per cent of the area used for construction. The five classes of exposure were chosen considering the 20th, 40th, 60th, 80th and 100th percentile of the calculated values of exposure in the basin. As expected, the highest values are reached in the areas where the main cities are located (Figure 5). The highest exposure is registered in the areas of Milan (mainly), Turin, Reggio Emilia, and Modena. The lowest values are registered in the mountainous areas of the basin (white areas in Figure 5).

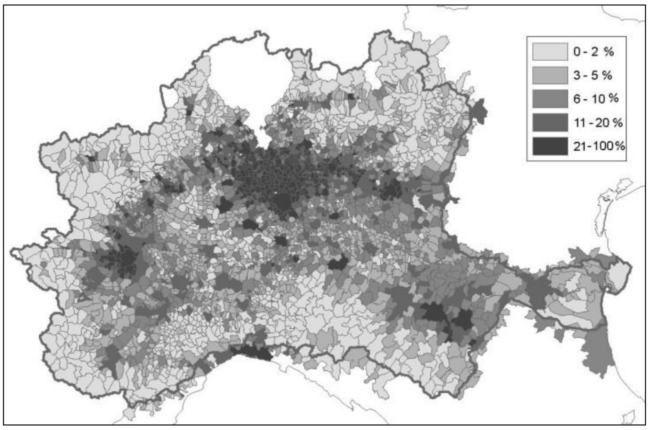

Figure 5: Exposure map of the municipalities in the Po River basin. Percentage of constructed area over the total municipality. Source: Authors' own elaboration based on CORINE Land Cover (2006).

2.5.3. Socio-demographic data

To the best of our knowledge there is not any spatially aggregated social vulnerability index available at basin level. Socio-demographic data produced by the National Institute of Statistics (ISTAT) are extensively available at national and regional scales, but less so at provincial and municipal level. Therefore, the variable selection for conducting a social vulnerability index for the study area has two considerations: (1) justification based on existing literature on its relevance to vulnerability and (2) availability of quality data from national source.

Based on these considerations the variables that were employed to capture social vulnerability are the following: population density (Tapsell et al 2002; Cutter et al 2003; Tapsell et al 2005; Tapsell et al 2010), percentage of population less than 18-years-old (King and MacGregor 2000; Cutter et al 2000; Cutter et al 2003; Tapsell et al 2005), percentage of population more than 65-years-old (King and MacGregor 2000; Cutter et al 2000; Cutter et al 2003; Tapsell et al 2005; De Marchi et al 2007), percentage of population not reaching the basic education (Cutter et al 2000; Cutter et al 2003; Tapsell et al 2005; De Marchi et al 2007), percentage of population reaching a high level of education (high school or more) (Cutter et al 2003; Tapsell et al 2005), percentage of foreigners (King and MacGregor 2000; Cutter et al 2003), employment rate (Cutter et al 2003; Tapsell et al 2005), percentage of population commuting to work by car or train (Brunckhorst et al 2011), percentage of population with a vehicle (Morrow 1997; Dunno 2011; Flanagan et al 2011). A summary of the selected criteria, and their availability, for assessing the flood risk in the basin is presented in Table 4.

Table 2 - Sources of data for the Po River basin

Domain	Criteria	Source	Project	Time Frame	Spatial Coverage	Resolution
Hazard	Flood and landslide prone areas	Po River Basin Dist. Aut.	PAI	1999-2010	Po basin	n.a.
Exposure	Land cover	ISPRA	CLC	2006	Italy	100m
Vulnerability	Pop. Density	ISTAT	Census	2001	Italy	Municipality
Vulnerability	Pop <18 years	ISTAT	Census	2001	Italy	Municipality
Vulnerability	Pop>65 years	ISTAT	Census	2001	Italy	Municipality
Vulnerability	Education	ISTAT	Census	2001	Italy	Municipality
Vulnerability	Foreigners	ISTAT	Census	2001	Italy	Municipality
Vulnerability	Car/Train Commuters	ISTAT	Census	2001	Italy	Municipality
Vulnerability	Pop. with a vehicle	ACI	Census	2001	Italy	Municipality
Vulnerability	Employment rate	ISTAT	Census	2001	Italy	Municipality

2.5.4. Aggregation of social vulnerability criteria and other risk components

Vulnerability of people is measured by a social vulnerability index. Due to the restriction of data because of privacy at the individual level, municipality level data have been used. The selected indicators in the risk vulnerability index are proxies of the vulnerable social groups (Cutter et al 2003; Tapsell et al 2010).

Vulnerability, *V*, has been calculated as the equally weighted sum of normalized criteria[1].

Normalisation and aggregation

The data referring to each of the indicators are different in unit and scale. This work adopts the Min-Max normalisation proposed by UNDP's Human Development Index (HDI) (UNDP, 2006). This methodology allows to standardize the values of the indicators and to obtain a final result ranging between 0 and 1 (ICRISAT, 2009)[2]. Criteria with decreasing effect on vulnerability level, such as education level and employment rate has been treated as (*1-x*).

After normalization, the indicators were aggregated to calculate the social vulnerability index, which represents the summation of equally weighted average sub-index scores (Simple Additive Weighting). The choice is motivated by the inability to concretely proof differences in the contribution of the single indicators in the overall determination of a Vulnerability Index (Cutter et al 2010).

Aggregation of risk components

For each municipality, social vulnerability, exposure and hazards components were finally aggregated using an equally weighted sum. Thus, the risk index is defined for each municipality from very low to very high.

2.6. Results

2.6.1. Vulnerability profile of the basin

After aggregating all the criteria, the vulnerability profile of the basin was calculated, which provides a good representation of the most vulnerable areas of the basin at municipality level (Figure 6). The final output classifies the municipalities into four categories obtained considering the quartiles of the results. The areas characterised by the lower level of vulnerability (ranging from 0.268 to 0.393) are

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[1] $V_j = \sum_{i=1}^{K} W_i X_{ij}$ with $W_i > 0$ for $i = 1,\ldots,K$ with $W_i = \frac{1}{K}$

V_j represents the vulnerability to flood for each municipality *j*, X_{ij} the set of the *i* indicators of vulnerability for each municipality *j*, and W_i the weight for each indicator *i,* where *i*=1,…, *K* with *K* being the total number of indicators.

[2] $x_{ij} = \frac{X_{ij} - \underset{i}{Min}\{X_{ij}\}}{\underset{i}{Max}\{X_{ij}\} - \underset{i}{Min}\{X_{ij}\}}$

located in the most remote and less populated areas, such as the Alpine regions of Piedmont (west part of the basin), Lombardy (north part of the basin) and the Apennine region of Emilia Romagna (south part of the basin) where the landscape is characterized by the presence of forests, national parks, and natural ecosystems. The situation is very different in Valle d'Aosta, where the level of vulnerability reaches the highest values (dark blue in Figure 6). This is explained by the fact that even if the density of the population could suggest a low level of vulnerability, its composition (e.g., age, education, presence of foreigners) leads to be classified as one of the highest vulnerable areas (ranging from 0.428 to 0.539). Other high vulnerable areas are located in the central of the basin, where the highest population density is reached.

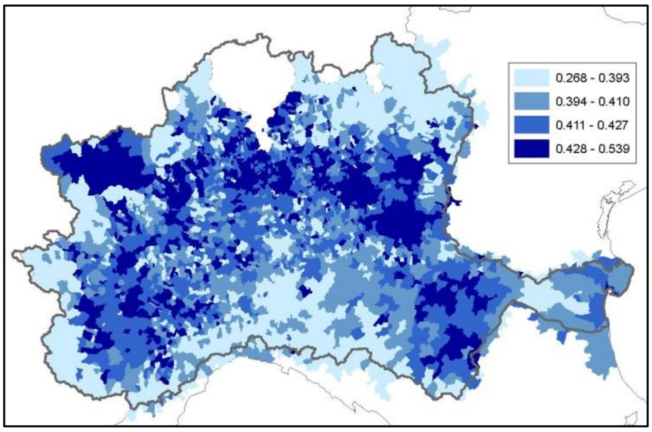

Figure 6: Vulnerability map of the municipalities in the Po River basin. Source: Authors' own elaboration based on ISTAT and ACI Data.

2.6.2. Risk profile of the basin

The combination of hazard, exposure and vulnerability, using equation (1) with equal weights, provides the risk profile of the basin (Figure 7). The map classifies the municipalities into five categories: very low, low, medium, high and very high. The five classes of risk were chosen considering the 20th, 40th, 60th, 80th and 100th percentiles of the calculated values of risk in the basin (Figure 6). The highest risk areas are located in the mountainous and in the most populated portions of the basin. Almost the entire Valle d'Aosta region is characterised by the highest risk, which is consistent with the high values of hazard and vulnerability for the specific area. The same is apparent for the metropolitan areas of Milan, Turin, Parma, Reggio Emilia and Modena. On the other hand, low and very low levels of risk were registered in the plain part of the basin, mainly driven by the low hazard.

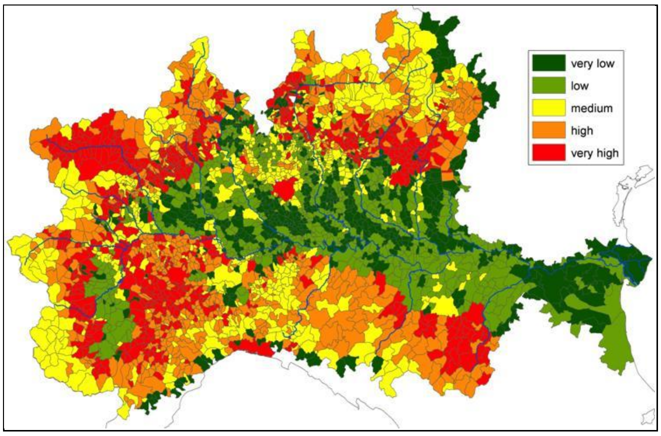

Figure 7: Risk map of the municipalities in the Po river basin. Source: Authors' own elaboration.

2.7. Conclusions

The new European policies on water management, European Water Framework Directive (WFD) and Flood Risk Management Directive, ask for better knowledge of risk, vulnerability and potential losses due to extreme hydrometeorologic events in the European basins. Several studies have been already performed in the Po River basin and Italy aiming to these objectives, however, none have included social vulnerability, which is fundamental to define the risk, as a factor. De Marchi et al (2007) considered social vulnerability in their work, but they focused on a limited area and a specific event. Through the analysis of available information on hazard exposure and socio-demographic data of the Po River Basin District, our study draws a possible methodology for understanding the spatial distribution of risk at municipality level. It is a first effort towards the inclusion of social vulnerability in the estimation of risk to hydrometeorologic extremes within the Po River basin.

However several factors still cause limitations to the implementation of the methodology described in this document. First is the resolution at municipality level, which could cause biases in the definition of hazard and exposure. To mitigate this further research efforts could provide downscaled risk profile to higher resolution other than municipality, including recent household data from the latest Census (2012) and from the National Register of Properties and Land. Second, socio-economic data availability is still scarce. Appropriate downscaling of aggregated information at larger scale (Labor Local Systems, Provinces, Regions, etc.) could be a source of additional information for the construction of improved dataset at municipality level, like in SoVI (Cutter et al 2003). Third, recent efforts in updating flooding maps, within the implementation of 2007/60/EC, will possibly provide better understanding of the hazard profile of the basin. Although this study was developed on Hazards of Place (HOP) model of vulnerability (Cutter, 1996) and Social Vulnerability Index (SoVI) (Cutter and others, 2003), it deviates from both methodologies in terms of risk component calculation approach. The inclusion of social vulnerability is based on selected indicators, like in HOP, but do not analyse larger set of variables like in SoVI. Hazard and exposure components are deduced from hydrological maps, from River Basin District Authority, aggregated at municipality level and land cover characteristics from the Environmental Protection Institute (ISPRA).

Since both components, river basin hydrological profile and regional land cover categorization at basin level, are in the process of revision for the implementation of Italian L.D. 49/2010, we believe that the inclusion of social vulnerability in the risk estimation at municipal level, provides better understating in the comparison between different geographic units within the basin. In addition to Po River basin, the methodology could be a prototype for other Italian hydrological districts, in the process of complying with EU Flood Risk Management Directive 2007/60/EC and Italian Decree L.D. 49/2010.

Acknowledgments: The research that brought to this Section was produced with the assistance of Dr. Jaroslav Mysiak within the PREEMPT project "Policy relevant assessment of socio-economic effects of droughts and floods", funded by European Commission, DG Humanitarian Aid & Civil Protection (ECHO), and the GEMINA Project, a collaboration effort by the Euro-Mediterranean Centre for Climate Change (CMCC) and the Italian Ministry of Environment Land and Sea.

3. Assessing direct and indirect economic impacts of a flood event through the integration of spatial and computable general equilibrium modelling

Note from the author: the research presented in this Section has been published as a journal article.

Carrera L., Standardi G., Bosello F., Mysiak J (2015). Assessing direct and indirect economic impacts of a flood event through the integration of spatial and computable general equilibrium modelling. Environmental Modelling and Software, Volume 63, Pages 109-122, ISSN 1364-8152, http://dx.doi.org/10.1016/j.envsoft.2014.09.016.

Abstract: We developed and tested an integrated methodology for assessing direct and indirect economic impacts of flooding. The methodology combines a spatial analysis of the damage to the physical stock with a general economic equilibrium approach using a regionally-calibrated (to Italy) version of a Computable General Equilibrium (CGE) global model. We applied the model to the 2000 Po river flood in Northern Italy. To account for the uncertainty in the induced effects on regional economies, we explored three disruption and two recovery scenarios. The results highlight that: i) the flood event produces indirect losses in the national economic system, which are a significant share of the direct losses, and ii) the methodology is able to capture both positive and negative economic effects of the disaster in different areas of the same country. The assessment of indirect impacts, in particular, is essential for a full understanding of the economic outcomes of natural disasters.

3.1. Introduction and background

Water-related extremes, such as floods and storms, account at the global level for the greatest share of natural disasters' inflicted economic damage and death toll (Jonkman and Kelman 2005; Kunreuther and Michel-kerjan 2007; United Nations International Strategy for Disaster Reduction Secretariat 2009). In Europe, according to NatCatService (MunichRE 2010), 80 percent of the economic losses caused by natural disasters that occurred during the period 1980-2009 were related to hydro-meteorological events (EEA 2010). Hydrological events only (i.e. flood and wet mass movements) account for 25 percent of the overall losses in the 32 European Environmental Agency (EEA) Member States, estimated as 414 billion Euro over the period 1980-2009 (in 2009 values) (EEA 2010).

Growing population and capital density, unsustainable development, inappropriate land use and climate change, threaten to intensify natural hazards' risk with even more concerning consequences for the environment and societies (IPCC 2012). Against this background the EEA warned that flood related losses will rise consistently in Europe (EEA 2012). According to Feyen et al. (2012), which calculated the expected annual damage (EAD) from river flooding events in Europe, current EAD of 6.4 billion Euro may increase by 2100 to 14 - 21.5 billion Euro (constant 2006 prices) depending on climate scenarios (Feyen et al 2012). Under the medium to high emission scenario A1B Rojas et al. (Rojas et al 2013) calculated that EAD might raise by the end of this century to around 97 billion Euro (constant 2006 prices undiscounted, considering both climate and socio-economic changes).

However, economic impacts of natural hazards are still poorly understood, particularly their indirect, wider and macro-economic effects. Typically estimates from the European Environmental Agency (EEA) (EEA 2012) and global disaster databases (i.e. the EM-DAT dataset managed by the Centre for Research on the Epidemiology of Disasters, the NatCatSERVICE dataset managed by Munich Reinsurance Company, and the Sigma dataset from Swiss Reinsurance Company) undervalue the full cost of disasters to societies and environment because most of the time they account for direct impacts only, with partial or incomplete consideration given to indirect, wider and macroeconomic effects.

Several efforts have been made to assess indirect impacts of disasters on national and regional economies (Cochrane 2004; Rose 2004; Messner et al 2007; Okuyama 2007; Green et al 2011; Przyluski and Hallegatte 2011) using different methodologies. These include amongst others: post event economic surveys (Kroll et al 1991; Pfurtscheller 2014; Molinari et al 2014), econometric models (Albala-Bertrand 1993; Noy and Nualsri 2007; Strobl 2010; Cavallo et al 2012), input-output (I-O) models (Okuyama et al 2004; Hallegatte 2008; Hallegatte et al 2011; Ranger et al 2011; Henriet et al 2012; Okuyama 2014), computable general equilibrium (CGE) models (Rose et al 1997; Rose and Liao 2005; Bosello et al 2006; Tsuchiya et al 2007; Berrittella et al 2007; Jonkhoff 2009; Pauw, K. et al 2011; Bosello et al 2012; Haddad and Teixeira 2013). Different methodologies have different advantages and disadvantages. Econometric models and post event surveys, if well specified and based upon data of a reasonable quality, can indeed quantify indirect effects on national/local GDP of extreme events with high levels of accuracy and scarce uncertainty in the assessment procedure (Przyluski and Hallegatte 2011). However they cannot describe the systemic economic channels through which they propagate within and between the economies affected. I-O and CGE models can do so (Moffatt and Hanley 2001; Rose 2004; Okuyama 2007; Hallegatte 2008). I-O models can reach a high analytical specificity, they can represent urban contexts as well as even smaller economic entities like natural parks or cities, but then they are usually missing the effect on the overall economy. Moreover I-O models cannot assess the impacts on the supply side, and do not allow for flexibility in the economic system which is indeed a characteristics of CGE models (Hallegatte 2008). CGE models are able to capture the feedback effects from the macro-economic context on the "markets" initially concerned (Rose 2004). Furthermore, in general equilibrium approaches the use of consistent accounting methodology for capturing economic flows overcome the problems of 'double-counting', often affecting the evaluation conducted through the application of partial equilibrium (Pauw, K. et al 2011). CGE models also offer in principle the possibility to conduct simulated counterfactual analyses, comparison between what happened and what would have happened in the absence of the catastrophic event. Nonetheless, CGE models have several limitations. They assume perfect markets and they are not able to capture non-market values (Pauw, K. et al 2011). Another important limitation of CGE models is their "coarse" investigation unit, usually the country. This may allow analysis of aggregated events or trends, but makes local analyses particularly challenging, especially for small to medium disasters.

Against this background, in this paper we propose the combination of a spatially based analysis with a CGE model, regionally calibrated to the Italian macro-regions North, Centre and South (Standardi et al 2014). Our sub-national version of the global CGE model allows to assess the regional impacts (at sub-national level), whilst maintaining the global scale of the economic system (e.g. global trading, international exports and imports, etc.).

Our aim is to couple the high resolution of spatial analysis (Zerger 2002) with the CGE models' systemic ability to capture economic interaction (Bosello et al 2006; Bosello et al 2012; Liang et al 2014), without pushing the CGE aggregation need too far to loose completely local specificities. We then apply our methodology to estimate the economic impacts at the sub-national and national level of a flood event that occurred in Northern Italy in October 2000. At country level the outputs of the model provide an indirect-direct losses ratio of 0.19-0.22. The model is also able to unravel the wider impact of the flood into differentiated effects in sub-national economies. Thus the indirect losses in the North are partially compensated by (small) economic gains in non-affected areas (Centre and South) because of the interconnectivity of the economic system, the mobility of productivity factors and substitution of goods. The propagation of impacts beyond national border is negligible and the EU level GDP is in practice unaffected.

The paper unfolds as follows: Section 2 briefly reviews the case study area and the flood event; Section 3 provides a comprehensive discussion on the conceptual framework and methodology, a description of the sample data and the integrated model; Section 4 presents and discusses the results; Section 5 concludes the document providing a critical review of the outcomes, in the broader context of flood impact assessment and disaster risk management.

3.2. Background information on the Po river October 2000 flood event

The Po river is located in Northern Italy, which includes eight Italian regions: Piedmont, Aosta Valley, Liguria, Lombardy, Trentino Alto Adige, Veneto, Friuli-Venezia Giulia, Emilia-Romagna. The area produces around 77 percent of the national Gross Domestic Product (GDP), with Lombardy having by far the largest economy (21 percent of national GDP), followed by Emilia-Romagna with 9 percent, Piedmont with 8 percent and Aosta Valley with 0.3 percent. Because of the strategic importance of the area, this paper analyses the economic impacts of the Po river flood that occurred in October 2000 in Piedmont, Aosta Valley and other downstream regions in the Northern Italy. Between 13th and 16th October 2000, a series of extreme precipitation events, up to 600 mm in 48 hours hit the Northwest of Italy leading to numerous inundations and landslides (Regione Piemonte 2000a; Regione Piemonte 2000b; Ratto et al 2003). The event is amongst the most significant that have occurred in Italy over the past decades. It caused 37 casualties and missing persons (27 in Italy and 10 in Switzerland) and economic damages of over 2.5 billion Euro, as reported by the Information System on Hydrogeological Disasters (IRPI), 5.2 billion Euro as reported by Guzzetti and Tonelli (2004) or 8.6 billion Euro as reported by the EM-DAT International Disasters Database (Centre for Research on the Epidemiology of Disasters - CRED). More than 40,000 people were evacuated and at least 3,000 lost their houses (Guzzetti and Tonelli 2004). The flood hit more than 700 municipalities and almost all main cities of Piedmont and Aosta Valley. All economic sectors were severely impacted, either directly through structural damage or indirectly through business interruptions. The flood caused significant damages to industries, transport infrastructures and urbanized areas. It led to lifelines interruptions, cutting-off major highways, regional and provincial roads. Milan-Turin and Turin-Aosta highways were severely damaged. Bridges were destroyed resulting in temporal isolation of small and medium sized towns (Tropeano and Turconi 2001). In several areas electricity, telecommunication, and drinking water supply services were interrupted for days – up to a week in Turin and other towns in the area (Tropeano and Turconi 2001). In addition to hitting the constructed areas, the flood caused serious damages to agriculture affecting livestock, crop production, farm structures, and farming facilities (Farinosi et al 2012).

3.3. Methodology

3.3.1. Conceptual framework

Our work aims to estimate the economic impacts of the Po river 2000 flood event. Because of the knowledge gap in indirect impact assessment, this paper focus on developing and testing an integrated methodology specifically aiming at their quantification. Therefore the direct impact assessment shall be considered instrumental to the indirect, and meaningful for comparison and validation of the outputs provided by the integrated spatial-CGE model. Hereinafter, we define the terminology used in the paper and the general conceptual framework with reference to relevant literature.

Meyer et al. (2013) divides the economic impacts of disasters in direct, business interruption, and indirect costs. Direct are the losses affecting humans, assets, property and any other objects in the areas that had physical contact with the flood (Merz et al 2010b; Meyer et al 2013). Business interruptions are those losses that occur to business directly affected by the hazard. They are often referred as primary indirect damages because they are induced by the interruption of business activities. Indirect losses occur inside and outside the flooded area (Messner et al 2007; Merz et al 2010b) and are caused by direct costs and/or business interruption costs (Przyluski and Hallegatte 2011). Indirect impacts are prompted by the physical stock of capital which is damaged, transmitted through the inter-linkages of economic systems (Cochrane 2004; Merz et al 2010b) and resulting in a disruption of economic flows (Rose 2004; Rose and Liao 2005). More in general at meso and macro scale, floods engender exogenous, internal or external (if international trade is affected) 'shocks' to economies, with far-reaching ripple effects. Beyond the direct structural damage caused by floods, the disaster-affected sectors are likely to curtail their activities and production, collect less revenues, lay-off staff, and postpone investments. These dynamics influence both the market and consumers' preferences. Direct losses set off a sequence of 'upstream' and 'downstream' reactions, which affect suppliers and customers. These ripple effects represent the indirect impacts of a disaster. Generally a flood event produces negative effects on the region directly affected but, on the larger scale, the event could produce positive and negative propagation effects in the economies of neighbouring and distant regions (Jonkhoff 2009). The final economic effects of all these feedbacks and rebounds are in our analysis summarized by GDP changes assessed by the CGE model. GDP changes thus represent the indirect economic effects triggered by the flood event on the economic system. Indeed in the CGE jargon GDP costs are often referred to as 'indirect' or 'higher order' cost as they do consider price reactions, potential inter-market factor substitution and demand switches.

Summarizing, in this paper we consider direct impacts as the physical damage to the stock, which is a quantity at a single point time (Rose 2004), and indirect impacts as the effect of a disaster to the flows, originated by the stock over time (Rose 2004), or the aggregation of business interruption costs and indirect costs as defined in Meyer et al. (2013), which our model is not able to distinguish separately. Our analysis is a comparative static exercise adopting a one-year timeframe. In our setup the adjustment from the pre to the post-disaster economy is instantaneous. We acknowledge the fact that effects of disasters can extend over longer periods of time (Cavallo et al 2012; Hallegatte 2014b) and that friction and inertia may affect the transition phases. Therefore our estimation of indirect impacts shall be considered as short-term effects only and may underestimate losses. Table 3 provides the description of our conceptual framework.

Table 3. Summary of our conceptual approach and expected output. IT is Italy, EU European Union, RoW Rest of the world.

Type of impact (our definition)	Main literature reference		Assessment tool	Expected output	Scale of analysis
	Meyer et al. 2013	Rose et al. 2004			
Direct	Direct cost	Stock of capital	Spatial analysis with depth-damage functions from Huizinga (2007)	Physical damage to the stock of capital represented by the full replacement cost (Euro)	250x250m
Indirect	Business interruption cost, indirect cost	Flows	Sub-national CGE model from Standardi et al. (2014)	Percent change in: i) production per economic sector, ii) sub-national (North, Centre, South), IT, EU, RoW GDP	Sub-national areas (North, Centre, South), IT, EU, RoW

3.3.2. Integration of the spatial and CGE models

The integrated model described in this paper (Figure 8) is conceptually divided into three parts: i) the spatial analysis of the flood event for the estimation of direct impacts and affected areas (km^2) per land use class of Corine Land Cover 2000 (CLC2000); ii) the spatial-CGE integration part which produce the input (damage to the primary factors productivity per economic sector) to 'shock' the CGE model; iii) and the CGE model simulation which provides the indirect impacts.

Going backwards (right to left) in the methodological map (Figure 8) we proceed as follows:

a) We estimate indirect impacts (production and GDP changes, monetary losses) by applying a 'shock' to the sub-national CGE model. The shock is provided by reducing (in percentage) the primary factors (capital, land and labour) productivity of the economic sectors in the flooded area (North), which are exogenous factors of the CGE model;

b) We derive changes in factors' productivity are derived (in the second part of the model) from the relation between land use and economic activities (described in 3.3.5.2). Hence, the percentage of flooded area per land use class in the North is translated into a reduction of capital and land productivity. The percentage of workers affected is translated into a reduction of labour productivity. For instance, if 10 percent of industrial areas in the North are flooded, we assume that 10 percent of the capital of the heavy manufacturing capital sector is damaged for a certain period of time. Assuming this period to be three months, the reduction to the capital productivity will be: 0.1 x (3/12).

Equation 1 and 2 describe how we estimate the impacts to capital, land and labour:

$$(1)\quad impact\ to\ the\ capital\ (land)_k\ [\%] = \frac{flooded\ area_i\ [km2]}{total\ area_i [km2]} \times \frac{duration\ impact\ [days]}{365\ [days]}$$

$$(2)\quad impact\ to\ the\ labour_k\ [\%] = \frac{affected\ workers_k}{total\ workers_k} \times \frac{duration\ impact\ [days]}{365\ [days]}$$

where:

i is the land use class (or the sum of land use classes) associated to the economic sector k (Table 7).

We estimate workers at the municipality level and apply the impact to the Northern Italy economy. If a sector is associated with more than one land use class, the areas are summed up.

c) We estimate the impact using equations (1) and (2) via the spatial analysis. Flood extension maps are intersected with CLC2000 to calculate the flooded surfaces per land use class (km^2). CLC2000 is also used to calculate the total surface of each land use class in the North (km^2). The percentage of flooded area per land use class is the ratio between the two. We derive the number of affected workers from the National Census 2001 data at municipality level (from ISTAT). In order to consider the wider impacts of the flood, particularly on transport infrastructures and commuters, we assume that all workers belonging to a municipality intersecting the flooded area are fully affected. We use the same dataset to calculate the total workers in the North. As before, the ratio between affected and total is the percentage of affected workers. We estimate the direct economic impacts with depth-damage functions (Huizinga 2007) on land use classes.

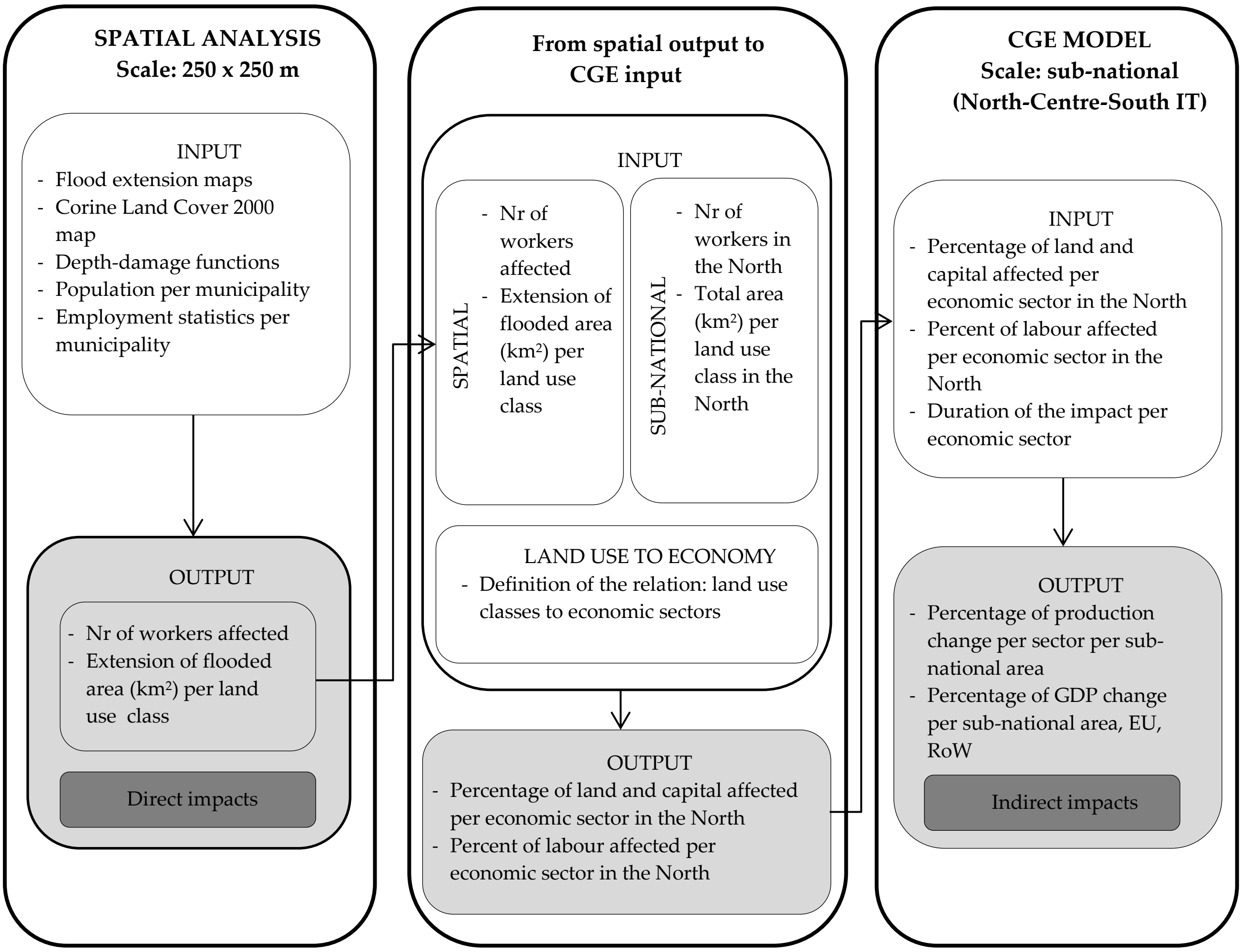

Figure 8: methodological map of the spatial-CGE integrated model.

3.3.3. Flood data sources

The flood extension data sources used in this paper are: the Piedmont Region, the Agency for Environmental Protection of Piedmont Region (ARPA Piedmont), the Aosta Valley Region, the Po River Basin Authority and ARPA Emilia Romagna. Piedmont and Aosta Valley were the most affected areas. Indeed, Piedmont produced and published a comprehensive impact assessment study (Regione Piemonte 2000a; Regione Piemonte 2000b), and both regions provided flood extension maps produced through on-site assessments and aerial photo interpretation. In the remaining regions (i.e. Lombardy and Emilia-Romagna) ARPA Emilia Romagna and the Po River Basin Authority provided information about the flood extension based on on-site observations. In these regions the flood recorded a maximum extension of the water confined within the 200 years return period dykes along the Po river. Figure 9 shows the area of study (Northern Italy) and the flood extension (in blue). These digital maps provide high resolution flood extension but no information on water depth.

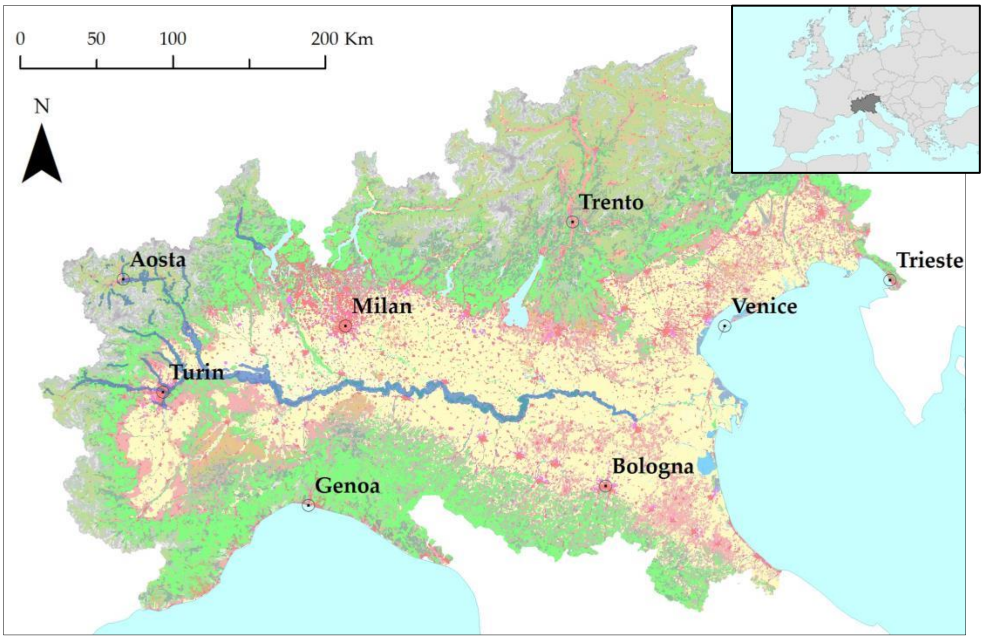

Figure 9. Po river 2000 flood extension (in blue) in Northern Italy, which is represented using Corine Land Cover map 2000. Red is mainly constructed area while yellow is agricultural land. Note: our analysis does not consider the delta of the Po river, which was not affected. Source: own elaboration on Corine Land Cover 2000, ISTAT, Region Piedmont, ARPA Piedmont, Region Aosta Valley, ARPA Emilia-Romagna and Po River Basin Authority.

3.3.4. Direct economic impact assessment

In recent years, an increasing number of studies have used land cover characteristics and water depth-damage functions for the assessment of the economic impacts of flood risk (Thieken et al 2008; Kreibich et al 2010; Feyen et al 2012; Rojas et al 2013; Balica et al 2013; Saint-Geours et al 2014), which is the most common methodology for the estimation of damage (Meyer and Messner

2005; Merz et al 2010b; Green et al 2011; Jongman et al 2012a). A depth-damage function provide the relationship between water depth and monetary damage for a specific land use type. The intersection of flood extension maps (with water depth sometimes complemented by other parameters such as velocity, duration, etc.) with land use maps of the flooded area, enables the calculation of direct damages of a flood event (Merz et al 2010b; Meyer et al 2013).

For consistency purposes in flood risk assessment amongst European River Basin Districts the European Commission's (EC) Joint Research Centre (JRC), Institute for Environment and Sustainability, developed a first Pan-European flood depth-damage function dataset for all EU27 Member States, including maximum damage values for each land use type (Huizinga 2007). This dataset has been used in pan-European flood risk assessments (Feyen et al 2012; Rojas et al 2013). Flood depth-damage functions are affected by a large degree of uncertainty in curves construction and the value of the assets (Merz et al 2010b; De Moel and Aerts 2011; Green et al 2011; Jongman et al 2012a). Moreover they provide country-scale curves only, without consideration given to local or regional differences. However given the primary focus of our study on indirect impacts and the limitation of information available (digitally available flood extension maps did not reported water depth, which we did not computed for) we found JRC's damage functions particularly suitable for our purposes. As described in Huizinga (2007) these damage functions do not represent depreciated values but full replacement cost of the damaged asset or good. Hence this approach may overestimate the damage (Merz et al 2010b), because it does not capture the traditional definition of value of a capital good, which is the present value of income of flow it generates over the remaining of its life period (Georgescu-Roegen 1993). However we believe that this method provides an acceptable estimation of the stock damaged by the flood event within the impacted area, i.e. the direct impact.

Our methodology proceeds as follows: we overlay CLC2000 map with the recorded flood extent, provided by the aggregation of the spatial layers available. The result is the flooded land, characterised by a specific use. Flooded areas are divided into five categories: urban continuous (CLC2000 code 1.1.1), urban discontinuous (1.1.2.), transport infrastructures (1.2.2, 1.2.3, 1.2.4.), industry and commercial (1.2.1.), agriculture (2.all).

The direct economic impact is a function of the type of land use (damage value per each land use), the level of the damage (damage factor, based on water depth), and the extension of the flooded area by land use type.

$$(3)\ Direct\ economic\ impact = \sum_{i=1}^{4} damage\ value_i \times damage\ factor_i \times extension\ of\ flooded\ area_i$$

where *i* = land use type: residential buildings (1), commercial and industrial (2), agriculture (3), transport infrastructure (4)

Table 4 shows the maximum damage values for some EU Member States and the damage factor range of values (from a minimum of 1 m water depth to a maximum of 6 m and over). In Huizinga's functions (2007), the maximum damage values were elaborated from existing studies across some EU countries and the average damage value per land use class was applied to other EU Member State scaled to GDP per capita (Jongman, 2012). The functions were built on observations from nine countries. In countries without prior damage function data (such as Italy), the average functions were used per for each land use class (Huizinga, 2007). The damage functions and maximum damage values are nationally homogenous, they do not account for regional differences.

Table 4. Maximum damage values (Euro/m^2 in 2006 prices) and damage factor range (from a minimum of 1m to a maximum of 6m and over) per land use class for selected EU countries. Source: own elaboration on Huizinga, 2007.

Max damage value - Area	**Residential building**	**Commerce**	**Industry**	**Road**	**Agriculture**
EU27	575	476	409	18	0.59
Italy	*618*	*511*	*440*	*20*	*0.63*
Luxembourg	1443	1195	1028	46	1.28
Germany	666	551	474	21	0.68
Netherlands	747	619	532	24	0.77
France	646	535	460	21	0.66
Damage factor (range)	0.4-1	0.3-1	0.3-1	0.42-1	0.55-1

As already mentioned, water depth is not provided in the digital version of our flood maps. To cover a range of potential impacts, we consider two scenarios of average water depth, 1m and 6m, the latter corresponding to the maximum damage value in Huizinga (2007). It is worth to highlight that in general, flood damage functions are characterised by large uncertainties in the maximum damage values, the depth damage curves as well as in the details of the damage categories (Merz and Thieken 2009; De Moel and Aerts 2011; De Moel et al 2012; Jongman et al 2012a; Saint-Geours et al 2014). Therefore our direct impact assessment could potentially be not very accurate (and potentially overestimated). However it provides an order of magnitude of direct losses to compare with the outputs of the indirect impact assessment.

Based on the aggregation of land classes, the following assumptions are considered: (1) since CLC2000 does not distinguish between industry and commercial, the average of the two is applied (i.e. 475.5 Euro/m^2); (2) because of their lower density, discontinuous urban area value is considered half of continuous (i.e. 309 Euro/m^2); (3) in the plain area of the valley roads are normally elevated from the average ground level. For this reason only a portion of road's damage value is considered for transport infrastructure surfaces (14 Euro/m^2). The same value was also extended to airports and railways.

3.3.5. Indirect economic impact assessment using the CGE model

Indirect economic impacts are assessed through the use of a CGE model. The family of models have been increasingly applied by national and international institutions to a wide range of issues, such as tax reforms, trade liberalization, energy policy, and recently, the economic effects of climate change impacts (Standardi et al 2014).

A CGE model is a system of equations which describes the behaviour of the economic agents (representative household and firm), the structure of the markets and the institutions, and the links between them. In the model mechanisms consumers maximize utility subject to an individual budget constrain. Firms maximize profit choosing the amount of inputs. Primary factors, such as land, capital, labour and natural resources, are owned by the household and are fixed in supply. The equilibrium in the market system is achieved when the demands of buyers match the supplies of sellers at prevailing prices in every market simultaneously. Global CGE trade models, such as the one used for our work, which is based on GTAP7 (Global Trade Analysis Project, reference year 2004) (Narayanan and Walmsley 2008) have a Walrasian structures. Money is neutral, factors are fully employed, and the markets are perfectly competitive. In addition, macro-economic closure is neoclassical as investments are driven by savings. Trade balance is determined endogenously. CGE model parameterization derives from a calibration procedure. That is, key behavioural parameters replicate the observed demand and supply relations in a given reference year. We followed the same procedure for the specification of sub-national relations in the CGE (see Appendix for the description of CES (*Constant Elasticity of Substitution*) and CET (*Constant Elasticity of Transformation*) functions).

As anticipated the time scale of our indirect impact analysis is one year and our CGE model is static. Each single ‘shock’ to the economic system (in our case to the productivity of primary factors of production such as capital, land, labour) translates into an impact on flows, i.e. a yearly disruption of regional/sectorial output and GDP. Within the year, we assume that the reduction in factors productivity is recovered within a selected timeframe depending on the economic sector (from 1 week of non-agriculture sectors to a maximum duration of 3 months for the agriculture sector). The uncertainty in production loss duration is dealt with considering three different duration scenarios based on authors’ judgement and literature (Kajitani and Tatano 2014; Pfurtscheller 2014). We acknowledge the fact that more extensive sensitivity analysis could better represent this type of uncertainty. The shock is enforced to the one year point of the disaster occurrence and does not influence precedent or subsequent years. No subsidies and post-disaster reconstruction are accounted for in the economic model, aside from the indirect effects on the duration of the recovery period. Inventories are also not considered.

3.3.5.1. The sub-national CGE model for Italy

Most global CGE models are limited in terms of the scale of analysis. They normally use of national panel data, with no detail at the sub-national level, which can be particularly important to capture highly spatially-heterogeneous flood impacts (Hallegatte 2012). Few CGE models report a sub-national detail at the same time keeping track of international relations[3]. Building such a tool requires a not negligible effort both in the database construction and in the modelling of the theoretical structure. We start from the GTAP model (Hertel, 1997), which presents the country as the highest geographical detail.

In order to derive a consistent sub-national economic description we used three datasets: (1) the GTAP 7 database (Narayanan and Walmsley 2008) which reports economic flows in the reference year 2004 for 57 sectors and 113 countries or groups of countries worldwide; (2) the sub-national dataset of ISTAT (*Italian National Statistical Institute*) from the same year, which provides information on value added, labour and land for the 20 Italian regions and 40 economic sectors; (3) ISTAT bilateral flows of carried goods (in tons) by mode of transportation (truck, rail, water and air) for the 20 Italian regions. We followed a three steps procedure: (a) we matched the 40 ISTAT sectors with the 10 GTAP sectors chosen in our aggregation and reported in Table 5. We distributed the Italian value added and primary factors in GTAP across the three Italian macro-regions (North, Centre and South) using the shares of ISTAT for value added, labour and land. Capital was computed as a difference between value added and labour. For the sectors that use natural resources we took the sub-national share of value added in those sector as a proxy; (b) we used the shares obtained from ISTAT transport data to split the sectorial GTAP Italian production between domestic sub-national demand and bilateral trade flows across Italian regions; (c) we adjusted the bilateral trade flows across Italian regions to make them consistent with the ISTAT data on the economic production by using the RAS statistical method (for more details see Standardi et al., 2014).

The modification of the model also requires some adjustments of the theoretical structure to incorporate the possibility of an increasing spatial mobility in both factors and goods market at the sub-country level, because both goods and factors usually move easier within the country than between countries (more details, including the main equations are described in the Appendix). In GTAP primary factors cannot move outside the country they belong to. This is partially justified in an international context, but it is not realistic within the same country, where for instance workers and

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[3] For a survey of the literature on sub-national CGE models see section 2 in Perali et al. (2012) and Rodriguez (2007).

capital can reallocate (at least partially) in other regions following push or pull economic factors. Moreover in a standard CGE model, the Armington assumption (Armington 1969) applies. It postulates that homologous domestic and imported goods are not perfectly substitutable in consumer preferences. This prevents unrealistic specialization phenomena and trade overflows. The values of the Armington elasticity are set by econometric estimations, which are carried out at the national level. Within national borders, the Armington assumption, that needs to be kept in order to avoid unrealistic specialization and trade between regions, needs to be realistically weakened (McCallum 1995). Armington elasticities were thus recalibrated at the sub-national level and the demand structure modified accounting for the higher product substitution inside than outside the Italian borders (for more details see Appendix and Standardi et el. 2014).

To account for the effects of these different assumptions we considered two recovery scenarios. The first scenario is represented by a rigid model that has the same theoretical structure and parameterization of GTAP. This means sub-national regions behave exactly like countries. As a result, factor endowments cannot move outside the sub-national region they belong and the trade in the sub-national region has the same Armington elasticity as in the standard GTAP model. The second model is a more flexible one. We introduced capital and labour mobility within Italy (endogenous factor supply at the sub-country level) through a CET function (see Appendix). As a result labour and capital can move across the Italian sub-national region after a shock in the economic system. We also modified the values of the Armington elasticity for the sub-national regions to take into account the fact that products are closer substitutes within the country than across countries[4].

The sectorial and geographical aggregations of the sub-national CGE model are shown in Tables 3 and 4.

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[4] For further details about the calibration of the sub-national parameters refer to the Appendix.

Table 5: CGE model sectors

CGE sectors
Grains and crops
Livestock meat products
Mining and extraction
Processed food
Textiles and clothing
Light manufacturing
Heavy manufacturing
Utilities and construction
Trade and communication
Other services

Table 6: regions of the CGE model

CGE regions	Description
North	Aosta Valley, Emilia-Romagna, Friuli-Venezia Giulia, Liguria, Lombardy, Piedmont, Trentino-Alto Adige, Veneto
Centre	Lazio, Marche, Toscana, Umbria
South	Abruzzo, Apulia, Basilicata, Campania, Calabria, Molise, Sardegna, Sicilia
EU	Rest of the European Union
ROW	All remaining countries in the world

3.3.5.2. Measuring indirect impacts

Table 7 provides an overview on the relation between the CGE sectors and the other datasets: land use (CLC2000), national and regional datasets on value added, land, labour, flows of transported goods (from ISTAT), and GTAP sectors.

Table 7: Construction of spatial-CGE model: CGE model sectors (left part of the table); GTAP sectors (global) and ISTAT databases (regional) (centre); CLC2000 and ISTAT database on labour (right).

CGE model Sector	Regional calibration of the CGE model		Estimation of the flood impact		
	GTAP model Sector	ISTAT databases Sector	CLC2000		ISTAT database on labour Sector
			name	code	
Grains and crops	Cereal grains; Crops nec; Oil seeds; Paddy rice; Plant-based fibers; Processed rice; Sugar cane; sugar beet; Vegetables; fruit; nuts; Wheat	Cereals; Citrus fruits; Flowers and potted plants; Fruits; Industrial vegetables;; Legumes; Olives; Other woody products; Pastures; Potatoes and vegetables; Wine	Agriculture	2.all subsets	Agriculture
Heavy manufacturing	Chemical, rubber, plastic prods; Electronic equipment; Ferrous metals; Machinery and equipment nec; Metals nec; Mineral products nec; Petroleum, coal products	Coke, refineries, chemical and pharmaceutical; Manufacturing of nonferrous minerals; Metal and metallic goods production; Wood, rubber, plastic factories and other manufacturing	Industry and commercial	1.2.1	Manufacture
Light manufacturing	Leather products; Manufactures nec; Metal products; Motor vehicles and parts; Paper products, publishing; Transport equipment nec; Wood products	Machinery and mechanical manufacturing, electric and optical equipment, transportation; Paper, printing and publishing; Tannery and leather	Industry and commercial	1.2.1	Manufacture
Livestock meat products	Animal products nec; Cattle, sheep, goats ,horses; Meat products nec; Meat: cattle, sheep, goats, horse; Raw milk; Wool, silk-worm cocoons	Eggs; Honey; Livestock; Meat; Milk	Agriculture	2.all subsets	Agriculture
Mining and extraction	Coal; Fishing; Forestry; Gas; Minerals nec; Oil	Fishing; Forestry; Minerals	none	none	Extraction
Other services	Business services nec; Dwellings; Financial services nec; Insurance; PubAdmin/Defence/Health/Educat; Recreation and other services	Brokering; Domestic assistance; Education; Healthcare and other social services; Other public, social and personal services; Public administration and defence; mandatory social insurances; Real estate, rentals, informatics, research and development, other professional and entrepreneurial activities	Urban	1.1.1, 1.1.2	Services
Processed food	Beverages and tobacco products; Dairy products; Food products nec; Sugar; Vegetable oils and fats	Food, beverages and tobacco	Industry and commercial	1.2.1.	Manufacture
Textiles and clothing	Textiles; Wearing apparel	Textile and wearing apparel	Industry and commercial	1.2.1	Manufacture
Trade and communication	Air transport; Communication; Sea transport; Trade; Transport nec	Hotels and restaurants; Logistics, storage and communications; Wholesale and trading; vehicle, motorbike and household appliance repairing	Urban	1.1.1, 1.1.2	Transportation
Utilities and construction	Construction; Electricity; Gas manufacture, distribution; Water	Construction; Production and distribution of electric energy, gas, steam and water	Transport infrastructures	1.2.2, 1.2.3, 1.2.4	Construction

We aggregate CLC2000 classes into four categories: agricultural, industrial/commercial, infrastructural, and urban. For the estimation of capital and land losses we associate the following land use class and economic sectors (Table 7): agriculture land is associated with grains and crops and livestock meat products; industrial/commercial land with processed food, textiles and clothing, light manufacturing and heavy manufacturing; infrastructure land with utilities and construction, which includes electricity, gas and water distribution; urban land with trade and communication and other services.

For the estimation of labour productivity losses we associate the six categories of workers defined by ISTAT (Italian National Statistics Institute) (agriculture, extraction, manufacture, construction, transport and services) to our CGE sectors (Table 7). We associate agriculture workers are associated with grains and crops and livestock meat products; extraction workers with mining and extraction; manufacture workers with processed food, textiles and clothing, light manufacturing and heavy manufacturing; construction workers with utilities and construction; transportation workers with trade and communication (in GTAP this sector includes also transport activities); services workers with other services.

Summarizing, we design the following inputs for the CGE model simulations:

a) As described in Section 3.3.2, we use the result of equation (1) as a proxy to quantify the land productivity loss in the sectors: grains and crops, and livestock meat products. We assume that the impact lasted for one, two, and three months[5];

b) By the same token and following equation (2), we compute labour productivity losses in agriculture are computed for a period of one, two, and three months of interrupted activity;

c) In all the other sector capital and labour follow equation (1) and (2), but assuming a shorter duration of impact: one, two, three weeks, as these sectors are less dependent upon land.

We compute the impact of the flood event for each sub-national region (North, Centre and South), Italy as a whole, the European Union (EU) and the rest of the world. Our outputs are: percentage change in real GDP and production in each sector. Absolute values have been computed using the Italian sub-national real GDP database (ISTAT) and scaled to Euro 2000 value using the World Development Indicator database (The World Bank).

3.4. Results and discussion

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[5] We are aware that these periods may not be accurate and need to be refined by additional studies. For our modelling purposes, this uncertainty was included considering three reasonable scenarios based on the specific characteristics of the livestock sector and seasonal farming (autumn-winter crops).

3.4.1. Direct economic impacts

Table 8 shows the flood affected areas by land use class.

Table 8: Flooded areas by land use classes and the share of the total flood extent.

Description	**Area [km2]**	**% flood extent**
Agriculture land	646.65	54.68
Urban	22.70	1.92
Urban continuous	614.21	0.05
Urban discontinuous	22.09	1.87
Industrial-commercial	5.71	0.48
Infrastructure	0.38	0.03
Other classes	507.19	42.89
Total	1,182.66	100.00

We calculate the damage to the physical stock as in equation (3) using Huizinga's (2007) damage functions (Table 9). We estimate the range of the damage for water depths of 1 and 6 meters and above, which correspond to the minimum and the maximum damage factors in Huizinga (2007).

Table 9. Direct economic impacts (Euro 2006 prices). DF is damage factor. Source: own elaboration on CLC2000, flood extension maps and Huizinga's (2007) damage functions.

Description	**Area [km2]**	**Damage [Euro/m2]**	**DF (1m)**	**DF (6m)**	**Total damage (1m) [Mil Euro]**	**Total damage (6m) [Mil Euro]**
Agriculture land	646.65	0.63	0.55	1	224.0	407.4
Urban	22.70					
Urban continuos	*0.61*	618.00	0.40	1	151.8	379.6
Urban discontinuos	*22.09*	309.00	0.40	1	2,730.7	6,826.8
Industrial-commercial	5.71	475.50	0.30	1	815.3	2,717.8
Infrastructure	0.38	14.00	0.42	1	2.3	5.4
Other classes	507.19	0.00	-	-	0	0
Total	**1,182.66**				**3,924.3**	**10,337.1**

Our results show that the analyzed flood event causes significant economic damages to all productive sectors and capital assets. We find that the largest share of losses occurs in the urban discontinuous and industrial/commercial areas, rather than in the urban continuous areas, as in other studies (Feyen et al 2012; Rojas et al 2013). We also register high level of losses in industrial/commercial areas. This is probably due to the fact that our flood extension map is based on real post-event observations rather than simulation results obtained from hydrological models. The former captures the real-world heterogeneity of protection levels across different land uses. For instance urban centres in the Northern Italy may be effectively protected, while industrial activities are often located in flood risk areas (Regione Piemonte 2000a; Regione Piemonte 2000b). Following the most conservative assumption our estimation calculates that the total damage amounts to almost 4 billion Euro in 2006 prices. Instead, with the highest damage factor, we estimate a total direct loss which exceeds 10,3 billion Euro (in 2006 prices).

3.4.2. Indirect economic impacts

Tables 10 and 11 describe the results of our spatial damage assessment feeding into the CGE model for indirect impact assessment.

Table 10: land affected by the flood in the Northern Italy.

DESCRIPTION	Total Area [km^2]	Flooded Area [km^2]	As % of Northern IT
All	119,521.15	673.24	0.56
Agriculture land	54,214.89	646.65	1.19
Urban	5,451.89	20.48	0.38
Industrial-commercial	1,196.13	5.71	0.48
Infrastructure	184.20	0.38	0.21

Table 11: number of workers affected by the flood. Note that if a municipality is entirely or partially affected by the flood, we consider the whole employed population as concerned. Sectors: agricultural (AGR), extraction (EXT), manufactures (MANIF), construction (CONS), transport (TRAN), services (SER), total workers (TOT). (Nr. Mun) is the number of municipalities affected. Source: own elaboration on ISTAT Census 2001.

DESCRIPTION	Nr. Mun	AGR	EXT	MANIF	CONS	TRAN	SERV	TOT
CGE sectors		*1, 2*	*3*	*4, 5, 6, 7*	*8*	*9*	*10*	
North total	4,541	435,290	116,047	3,259,352	867,645	497,706	5,817,653	10,993,693
North Flooded	367	33,377	13,928	307,878	79,221	51,378	601,462	1,087,244
North Flooded (%)	8	8	12	9	9	10	10	10

The two tables are the input data of the CGE simulations. Six simulations are run in total, using three disruption duration scenarios on two post-disaster recovery scenarios (the rigid and the flexible model). Results are shown in Figure 10. The North is the most affected area in both models, with the flexible one leading to higher losses. The flood has small to no impact on the Centre and the South in the rigid model due to the low market integration assumed (for this reason they are not reported in Figure 10).

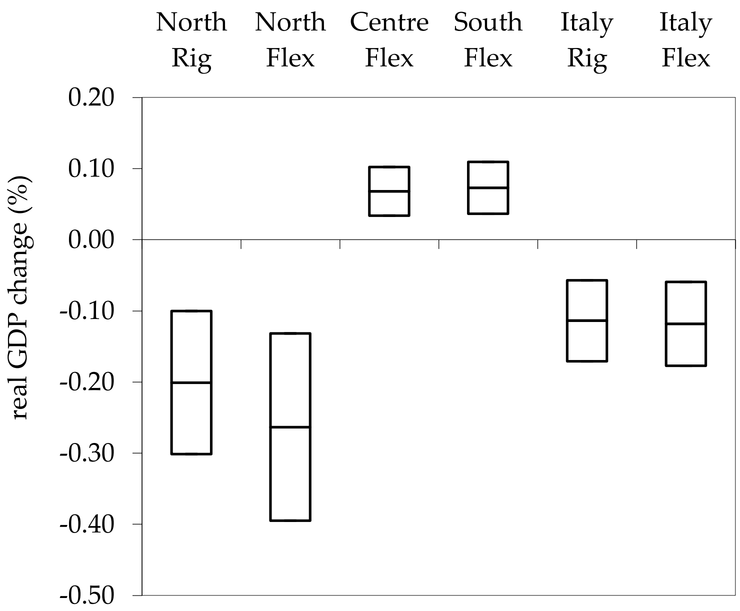

Figure 10: range of sub-national and national GDP variations (in percentage of real GDP) for different type of models: rigid = rig, flexible = flex, depending on the different duration of the impact. Centre and South Rig are not reported because the change is null.

In the flexible specification the Northern consumer and firm can more easily shift their purchases toward the Centre and the South. The consequence is a redistribution of the GDP from the North to the South and the Centre, which experience positive economic effects. Interestingly, results for Italy as a whole are similar both in the rigid and the flexible model. On the one hand this points out a comfortable robustness in the aggregated results. Introducing regional specificities does not transform entirely the economic pattern of the Italian supply and demands systems nor their response to shocks. On the other hand, it highlights the importance of introducing the regional analysis to capture relevant distributional effects. As expected, given the scale of the initial shock and the size of the economies involved, the impacts on the EU and the rest of the world are negligible (see further on this (Merz et al 2010b)), though not reported.

It is worth noting that the Centre and the South do not compensate the GDP and production loss in the North in the flexible model. In this version of the model the loss of productivity in the North (given by the flood impact) induces two mechanisms: i) a relocation of capital and labour from the North to the Centre and the South, where the demand for primary factors is not negatively affected and returns are higher; ii) the increase of the demand in the North for goods produced in the Centre and the South, allowed by the greater product substitutability deriving from the increase of the Armington elasticities. The result is that losses increase in the North, whereas Centre and South gain. As already mentioned, the aggregated effect in Italy is negative and very similar to the rigid version of the model, but the geographical distribution is more uneven.

The model also offers disaggregated sectorial results (Figure 11). In the North the most affected sectors are grains and crops, and livestock meat products, both in the rigid and flexible model. The same sectors in the Centre and the South increase their production both in the rigid and flexible model, with larger gains in the flexible model.

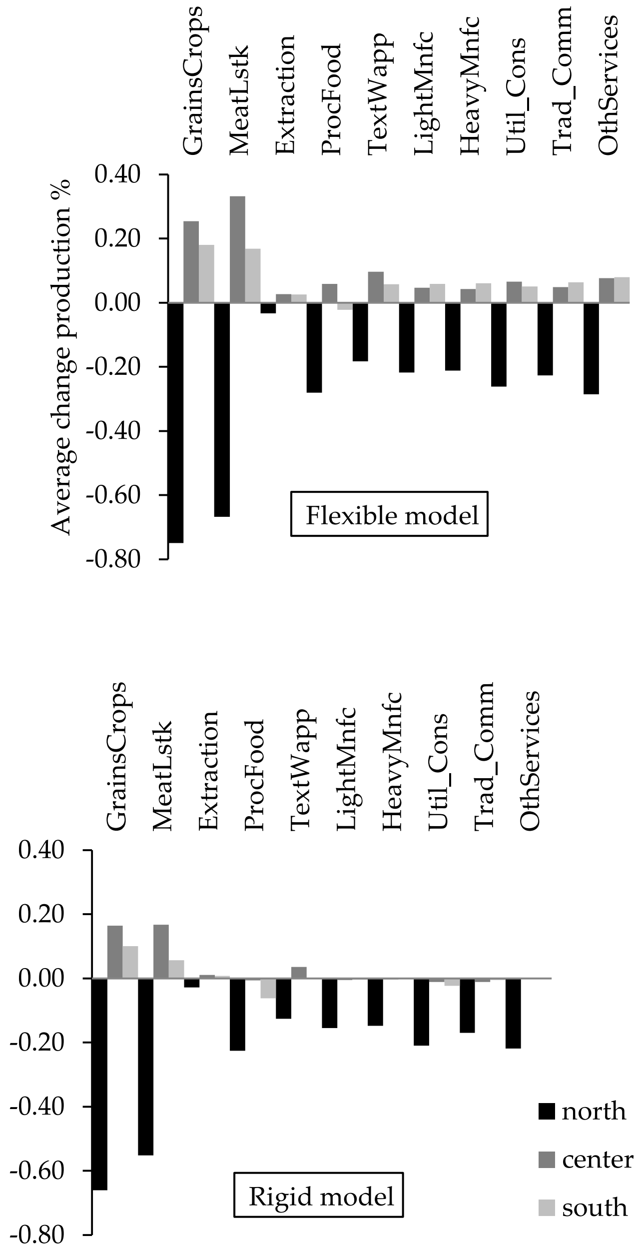

Figure 11: inter-sectorial distribution of the impacts: percentage of production variation in the North, Centre and South of Italy.

We estimate the indirect losses in the North to range from 644 million to 2,537 million Euro (in 2000 values), depending on the type of the model (rigid-flexible) and the duration of the disruption (Figure 12). Using the flexible model, due to the mobility factors a slightly positive effect is recorded in the Centre and the South. The indirect losses on Italy as a whole ranges from 647 to 1,955 million Euro (in 2000 values).

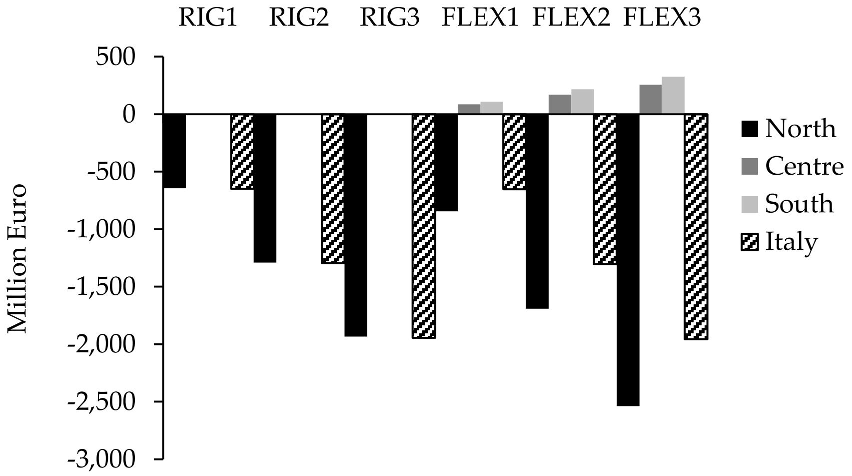

Figure 12: indirect economic impacts (2000 Euro value). Rig is the rigid model, while Flex is the flexible model. Numbers define the duration of the impact. (1) 1 months for agriculture and 1 week for other sectors; (2) 2 months for agriculture and 2 week for other sectors; (3) 3 months for agriculture and 3 weeks for other sectors. Economic losses are expresses in million Euro 2000 value. In the rigid model the impacts in the Centre and South are negligible, hence not reported.

3.5. Discussion of results

Indirect losses at country level represent a significant share of direct losses, which according to our estimation range from 3.3 to 8.8 billion Euro (in 2000 value). At country level both the rigid and the flexible models provide similar results of indirect losses. In the flexible model, the larger negative impact to the Northern economy is partially compensated by a positive effect in the other regions (Centre and South). It is a good signal that the flexible model is better designed to capture also positive effects of disasters, keeping constant the total indirect economic loss at country level.

Figure 6 shows the range of the results in terms of absolute losses. Direct impacts depend on the assumptions made with respect to the flood water depth. Indirect impacts are influenced by the duration of the impact on the productivity. Monetary values are actualized to Euro 2000 values, assuming the economic system of 2000 being similar to the economic system in 2004 (the CGE model base year).

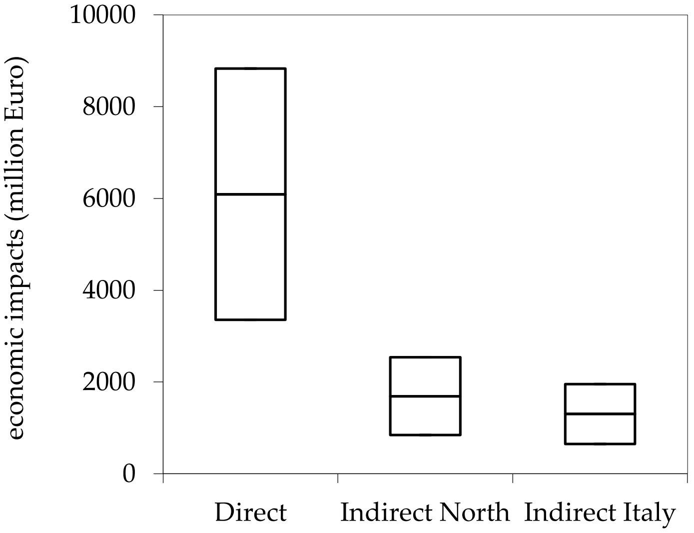

Figure 13: range of direct and indirect losses (in the North and Italy as a whole) using the flexible model. Values are given in million Euro 2000 value.

Because of the objective impossibility to work with a non-disaster counterfactual, the validation of our results is extremely difficult. Empirical evidence of changes in the regional and national economy and production are not available. We thus report some comparison with the literature conducting similar experiments. In our estimations, the ratio between indirect (at country level) and direct losses is around 0.19-0.22. Compared to the EM-DAT loss data for the same event (8.6 billion Euro) our indirect loss at country level ranges from 7 to 22 percent. The EMDAT dataset is reported to be a (not always transparent) combination of direct and indirect impacts. Other studies on indirect impact assessment of natural disasters provide figures in the same order of magnitude. For example, indirect economic losses in Louisiana after Katrina were estimated as 42 billion US$ compared to 107 billion US$ direct losses, that is 39 percent (Hallegatte 2008). The assessment of the indirect losses caused by sea level rise and storm surge in Copenhagen associated to a potential direct loss of 9,300 million Euro, provided an indirect loss of 747 million Euro, which is a ratio of 0.08 (Hallegatte et al 2011). These studies also highlight a clear nonlinear increasing relation between indirect and direct losses (Przyluski and Hallegatte 2011) which are also highly site- and hazard-specific. We acknowledge that additional research could corroborate our results, e.g. post-event econometric analysis to avoid noise and other perturbations existing in the annual production datasets (ISTAT).

3.6. Conclusion and policy implications

The economic analysis of natural hazard (notably flood) impacts focuses far too often on the direct damage to physical assets only, neglecting the wider indirect losses set off by the former. The global disaster databases such as EM-DAT do little to disentangle the direct from the higher order losses. Hence, the full social cost of natural hazards remains poorly understood. In a world of growing interdependency of national economies, an improved acquaintance of indirect economic losses is an essential prerequisite for a full appreciation of hazard risk.

In this paper, we examined a combination of spatially explicit damage assessment with macroeconomic loss propagation using a regionally calibrated version of a global CGE model. We applied the model on example of the destructive Po river flood that occurred in October 2000 in Piedmont, Aosta Valley, and other downstream regions in the Northern Italy. Paying due attention to the uncertainty regarding the length of disruption and the aftermath recovery, we analysed three scenarios of productivity falloff and two scenarios of inter-sectorial recovery. The direct flood damage was estimated by spatially explicit flood depth-damage functions over aggregated land use classes. The result of the spatial analysis were used to 'shock' the regional economy in the Northern Italy by weakening the primary factors' productivity (capital, land and labour) that are exogenous parameters of the CGE model. To account for the regional effects of the revisited event, we disaggregated a global CGE model with a country resolution to sub-national units, i.e. groups of regions almost equivalent the NUTS1 level. We also modified factors' mobility and substitutability of goods in consumers' preferences accordingly. The flood impacts were estimated in terms of the real GDP and the production changes for each economic sector in the North, Centre and South of Italy, Italy as a whole, the rest of Europe, and the rest of the world.

The results are considerable both in absolute and relative terms. We estimated direct impacts to range between 3.3 to 8.8 billion Euro (in 2000 values) depending on water depth assumptions. The indirect impacts were estimated as falling between 0.64 and 1.95 billion Euro (in 2000 values), depending on the controlled flexibility of substitution and mobility (rigid-flexible) and the length of productivity falloff. The approximated indirect losses amount to around one fifth (19 to 22 percent) of the direct losses, depending on the assumptions made. Considering the limitation of existing empirical information on 2000 Piedmont flood, our estimations match remarkably the results of other studies. The regionally disaggregated CGE model is instrumental to tracing down the transfer of disaster's effects across regions. The flexible version of the model is able to unravel the impact of a disaster into differentiated effects in sub-national economies, positive or negative as they may be depending on the location of the event.

Our analysis suggests that indirect losses play an important role in the full social costs of floods. The methodology detailed in this paper is applicable to other natural hazards (e.g. storm surges, forest fires, earthquakes, volcanic eruptions, avalanches, etc.) and/or countries and regions. Although data intensive and time consuming, the construction of a Pan-European CGE model disaggregated to NUTS2 level would make the indirect assessment more precise and sensitive to the regional differences of the hardship suffered. As a result, the EU disaster risk reduction policies would be better informed by empirical evidence, as highlighted in the EC (EC 2009), EEA (EEA 2013) and De Groeve (De Groeve et al 2013). The policies benefiting from a more comprehensive risk analysis include the EU Flood Directive (2007/60/EC), the EU Solidarity and Structural Funds (De Groeve et al 2013), and the Climate Change Adaptation (EC 2013).

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3.7. Appendix: the Italian sub-national CGE model

3.7.1. Supply

The value added in the standard GTAP model originates from five primary factors: land, natural resources, unskilled labour, skilled labour and capital. All the sectors use labour and capital while only some use land and natural resources (agriculture and mining-related sectors, respectively). Land and natural resources supply is sluggish across sectors while labour and capital are perfectly mobile. All the primary factors are spatially immobile. For our sub-national context, we assume the following:

a) Primary factors sectorial mobility does not change.

b) Land and natural resources remain spatially immobile at the sub-national level.

c) Sub-national unskilled labour, skilled labour and capital supply is geographically sluggish within Italy and still immobile with respect to the rest of Europe and the rest of the world.

The third assumption is new with respect to the standard GTAP model. It is implemented through a CET (*Constant Elasticity of Transformation*) function: as a result, workers and capital can move outside the Italian region they belong to in response to economic shocks.

First order conditions of the CET supply function and the formula to determine the national price of the endowment (shadow price) are given in the equations 1-6, where QL, QH, QK, PL, PH, and PK represent, respectively, the quantity of supplied unskilled labour, skilled labour, capital and the associated prices in the sub-national region. ITA and *r* are, respectively, the unique Italian aggregate index and the sub-national index. The parameters σ_L, σ_H and σ_K are the elasticity of substitution of the endowment supply, they are a measure of geographical mobility. Increasing the absolute value of these parameters means increasing the factors mobility within Italy. At this stage, we make the hypothesis that $\sigma_L = \sigma_H = \sigma_K$.

$$QL_r = QL_{ITA}\left(\frac{PL_{ITA}}{PL_r}\right)^{\sigma_L} \quad \text{with}\, \sigma_L < 0 \tag{1}$$

$$\sum_r QL_r PL_r = QL_{ITA} PL_{ITA} \tag{2}$$

$$QH_r = QH_{ITA}\left(\frac{PH_{ITA}}{PH_r}\right)^{\sigma_H} \quad \text{with}\, \sigma_H < 0 \tag{3}$$

$$\sum_r QH_r PH_r = QH_{ITA} PH_{ITA} \tag{4}$$

$$QK_r = QK_{ITA}\left(\frac{PK_{ITA}}{PK_r}\right)^{\sigma_K} \quad \text{with}\, \sigma_K < 0 \tag{5}$$

$$\sum_r QK_r PK_r = QK_{ITA} PK_{ITA} \tag{6}$$

The value of σ_K, σ_L and σ_H ranges from 0 to -1. No doubt arises for the case of perfect factor immobility ($\sigma_K = \sigma_L = \sigma_H$) as the value immediately derives from the economic theory. In the case of imperfect factor mobility we base our guess on the sensitivity analysis carried out in Standardi et al. (2014), which has shown as results are more sensitive for values included between 0 and -5. For this reason and given the fact that we are not considering long run effects but only effects which take place within a year, the value is set to be equal to -1. This is to avoid unrealistic changes in the labor and capital supply. However we are aware that an econometric estimation would be worthy to get more robust guess.

3.7.2. Demand

In the standard GTAP model the demand side is composed by private consumption, government spending and intermediate goods. The demand tree follows a double nest. The first nest links domestic demand and aggregate foreign imports of a specific commodity (irrespective of origin country) for each agent (households, government, firms). The second nest differentiates foreign imports according to the geographical origin. The second model improvement thus consists in modifying the demand tree in order to make sub-national products closer substitutes among them than the foreign products.

To achieve this goal we insert four additional parameters σ_{ARM1}, σ_{IMP1}, σ_{ARM2} and σ_{IMP2}. The parameters σ_{ARM} and σ_{IMP} are the Armington elasticities in the standard GTAP model representing in the country or group of countries the substitution between the national product and the aggregate foreign product and the substitution across foreign products which have different geographical origin; σ_{ARM1} and σ_{IMP1} are the Armington elasticities representing in the sub-national region the substitution between the national product and the aggregate foreign product and the substitution across foreign products which have different geographical origin; σ_{ARM2} and σ_{IMP2} are the Armington elasticities representing in the sub-national region the substitution between the sub-national product and the aggregate product coming from the other sub-national regions and the substitution across products coming from the other sub-national regions.

We use CES (*constant elasticity of substitution*) functions to model the inter-national and intra-national demands. As the following equations apply to all sectors in the same manner, for sake of algebraic simplicity we do not consider a sector index in the rest of this appendix.

Q, QD and QM, represent, respectively, the quantity of total, domestic and imported good demanded by households, government or firms in the country or group of countries, represented by index *c*. QU, QDU and QMU are, respectively, total, national and international imported good by households, government or firms in the sub-national region *r* (the suffix U stands for upper level).

QDL and QML represent the domestic and intra-national imported good in the sub-national region (the suffix L stands for lower level). P, PCD, PM, PU, PDU, PMU, PDL and PML are the associated prices.

The equations (7) and (8) show the mathematics behind the standard GTAP trade structure (still valid for rest of Europe and rest of the world in our model), the equations (9), (10), (11) and (12) describe the new structure for the sub-national regions (North, Centre and South of Italy):

$$\mathrm{QD_c} = \mathrm{Q_c}\left(\frac{\mathrm{P_c}}{\mathrm{PD_c}}\right)^{\sigma_{\mathrm{ARM}}} \quad \text{with}\,\sigma_{\mathrm{ARM}} > 0 \tag{7}$$

$$\mathrm{QM_c} = \mathrm{Q}_c\left(\frac{\mathrm{P_c}}{\mathrm{PM_c}}\right)^{\sigma_{\mathrm{ARM}}} \quad \text{with}\,\sigma_{\mathrm{ARM}} > 0 \tag{8}$$

$$\mathrm{QDU_r} = \mathrm{QU_r}\left(\frac{\mathrm{PU_r}}{\mathrm{PDU_r}}\right)^{\sigma_{\mathrm{ARM1}}} \quad \text{with}\,\sigma_{\mathrm{ARM1}} > 0 \tag{9}$$

$$\mathrm{QMU_r} = \mathrm{QU}_r\left(\frac{\mathrm{PU_r}}{\mathrm{PMU_r}}\right)^{\sigma_{\mathrm{ARM1}}} \quad \text{with}\,\sigma_{\mathrm{ARM1}} > 0 \tag{10}$$

$$\mathrm{QDL_r} = \mathrm{QDU_r}\left(\frac{\mathrm{PDU_r}}{\mathrm{PDL_r}}\right)^{\sigma_{\mathrm{ARM2}}} \quad \text{with}\,\sigma_{\mathrm{ARM2}} > 0 \tag{11}$$

$$\mathrm{QML_r} = \mathrm{QDU}_r\left(\frac{\mathrm{PDU_r}}{\mathrm{PML_r}}\right)^{\sigma_{\mathrm{ARM2}}} \quad \text{with}\,\sigma_{\mathrm{ARM2}} > 0 \tag{12}$$

The value of σ_{ARM} and σ_{IMP} stems from GTAP, which, in turn, derive them by econometric estimation (Hertel, 1997).

In the rigid model two relations characterise the four parameters:

$\sigma_{\mathrm{ARM}} = \sigma_{\mathrm{ARM1}} = \sigma_{\mathrm{ARM2}}$

$\sigma_{\mathrm{IMP}} = \sigma_{\mathrm{IMP1}} = \sigma_{\mathrm{IMP2}}$

In the flexible model the relations are following:

$\sigma_{\mathrm{ARM}} = \sigma_{\mathrm{ARM1}} = 2/3*\sigma_{\mathrm{ARM2}}$

$\sigma_{\mathrm{IMP}} = \sigma_{\mathrm{IMP1}} = 2/3*\sigma_{\mathrm{IMP2}}$

These relations take into account the increased product substitutability at the sub-national level. The factor 2/3 is somewhat arbitrary. However for values smaller than 2/3 the algorithm has troubles to converge to the optimal solution. As a consequence we can interpret it as a threshold to model substitution across sub-national goods.

As in the case of factor market, econometric estimation would be more appropriate to assess the new Armington elasticities. Unfortunately, to the best of our knowledge they are not available for this kind of problem and we are forced to do some simplification.

4. The economics of flood risk in Italy under current and future climate

Note from the author: the research presented in this Section is based on a paper *in preparation for submission* to the Journal *Climatic Change*

Abstract: An integrated impact assessment methodology is developed and applied to estimate current and future economic impacts of flood risk in Italy. The methodology combines an high resolution spatial approach with a regionally-calibrated version of a global Computable General Equilibrium (CGE) model. The economic effects are estimated per region, in terms of Gross Regional Product and production change from the 1961 till 2100. Climate change effects are built on 12 climate experiments under the SRES-A1B emission scenario. Results are provided for two risk mitigation scenarios. In Italy, the current aggregated ensemble-based expected annual output loss is 164 million Euro/year. Because of climate change, by the end of the century, EAOL might exceed 600 million Euro/year. Appropriate adaption measures may reduce economic losses by three times. We argue that the assessment of output losses, which represents the wider effect of a disaster on the economy, has significant policy relevance which shall not be neglected further in disaster's accountancy.

4.1. Introduction

The observation of many climate and weather events shows that globally, extremes have changed since 1950 (IPCC 2013b). According to the IPCC (2013) the anthropogenic influence has likely affected the global water cycle since 1960. This influence has modified precipitation patterns over land and increased the intensity of heavy precipitations (IPCC 2013b). Although the frequency and intensity of extreme precipitations have great variability in location and time, it is likely that heavy precipitation events have increased in Europe (IPCC 2013b). The probability of enormous economic losses from hydrological disasters is substantial (EEA 2012; UNISDR 2013; Jongman et al 2014; IPCC 2014c). The 2014 NatCatService Annual report (Munich Re 2014) reveals a substantial deviation of flood losses in 2013 over the global aggregated losses (37 percent against the 22 percent in the period 1980-2012). Although the signal is statistically insignificant, it is worth to highlight that globally the most costly natural disaster of 2013 were the Central-Eastern European floods of May and June, accounting for a loss 15 billion US dollars (Munich Re 2014). Munich Re (2014) dataset also shows a linear increasing trend in the frequency of flood events and the inflicted economic damage. However, there is disagreement in the literature about the anthropogenic climate influence on this trend. Barredo (2009) shows that, if flood losses are normalized to time-variant socio-economic factors (e.g. population, wealth, inflation), there is no detectable sign of human induced climate change effects in Europe (Barredo 2009). On the other hand, Barthlet and Neumayer (2011) analysis of normalized trends of insured losses shows a positive trend of flood losses in the United States over the period 1973-2008 (Barthel and Neumayer 2011). On the same line of Barredo (2009), Visser et al. (2014) argues that the exposure of people and economic activities are the main drivers of increasing losses due to weather related events (Visser et al 2014). This suggests that climate change and increasing disaster losses is not a straightforward relation, at least for the past.

If the detection and attribution of climate change effects on flood losses trend is still bleary, future projections are even more uncertain. The AR5 of the IPPC confirms that, because of the increasing global temperature caused by anthropogenic activities, it is very likely that extreme precipitation events will occur more frequently and with stronger intensity by the end of this century (IPCC 2013b). Growing economies and capital density, increasing demography and inappropriate land use will further expose societies to natural hazards, increasing flood risk and consequent losses (IPCC 2012; Hallegatte 2014b). Several authors have already stressed the importance of the link between development, land degradation and flood risk (Pottier et al 2005; WMO 2008; Wheater and Evans 2009; De Moel and Aerts 2011; Hallegatte et al 2013; Hallegatte 2014b). Moreover The European Environmental Agency (EEA) warned against increasing economic impacts (EEA 2012). Some studies already provided projection of future potential losses of fluvial flooding in Europe. For example, Feyen (2012) estimated that the current aggregated expected annual loss (EAL) in Europe is 6.4 billion Euro/year (in 2006 prices) (Feyen et al 2012). Under the SRES B2 medium to low emission scenario the EAL might increase by the end of the century to 14 billion Euro/year (Feyen et al 2012) and under the SRES A1B medium to high emission scenario to 97 billion Euro/year, considering both climate and socio-economic changes (Rojas et al 2013). These figures refer to ‘direct’ losses, i.e the damage to the stock of capital or the so called asset loss, which is the estimation of the reconstruction-rehabilitation cost of the assets totally or partially destroyed. These impacts have been extensively investigated in the literature, using different methodologies. The most common makes use of flood depth-damage functions, which provide a damage per meter square based on water depth and land use (Thieken et al 2008; Kreibich et al 2010; Feyen et al 2012; Rojas et al 2013; Balica et al 2013; Aerts et al 2013b; De Moel et al 2014; Saint-Geours et al 2014).

However these methodologies do not capture the full cost of disasters. Over the past years an increasing number of scholars have highlighted the importance of assessing the economic flows which are diverted or interrupted, and the overall reaction of the economic system in the aftermath of a disaster (Cochrane 2004; Rose 2004; Messner et al 2007; Okuyama 2007; Green et al 2011; Przyluski and Hallegatte 2011). Few methodologies have been developed and applied: post event economic surveys (Kroll et al 1991; Pfurtscheller 2014; Molinari et al 2014), econometric models (Albala-Bertrand 1993; Noy and Nualsri 2007; Strobl 2010; Cavallo et al 2012), input-output (I-O) models (Okuyama et al 2004; Hallegatte 2008; Hallegatte et al 2011; Ranger et al 2011; Henriet et al 2012; Okuyama 2014), computable general equilibrium (CGE) models (Rose et al 1997; Rose and Liao 2005; Bosello et al 2006; Tsuchiya et al 2007; Berrittella et al 2007; Jonkhoff 2009; Pauw, K. et al 2011; Bosello et al 2012; Haddad and Teixeira 2013; Carrera et al 2015). However a commonly accepted methodology is not yet available, neither a systematic recording of output losses. Although the evidence of significant output losses is well known, these type of estimations are rarely considered in disaster's loss accountancy.

Against this background, this paper propose the integration of a spatially based model of the physical drivers of flood risk (hazard and exposure), with a regionally-calibrated global Computable General Equilibrium (CGE) model of Italy, to estimate expected annual output losses (EAOL) per region (NUTS2) over the time period 1980-2080.

Italy is exceptionally prone to flood risk. The National Research Council's AVI (Damaged Urban Areas) archive reports, over the period 1900-2002 (Guzzetti and Tonelli 2004), more the 4,500 hydrogeological events and more than 10,000 fatalities. Moreover, according to the national Institute for Environmental Protection and Research (ISPRA), the empirical records over the last decades show an average annual asset loss of around 1 billion Euro (…prices) (ISPRA 2010). This estimation is in line with the EAL estimated by Feyen et al (2012) as 800 million Euro/year (2006 prices). According to the studies already mentioned, in Italy climate and socio-economic changes are projected to increase losses by the end of century to 2,400-2,900 million Euro/year (undiscounted 2006 prices) under the SRES A2 and SRES B2 emission scenarios respectively (Feyen et al 2012), and up to 14,000 million Euro/year (undiscounted 2006 prices) under the SRES A1B emission scenario (Rojas et al 2013).

This study makes use of a global CGE model to estimate expected output losses. CGE models have been increasingly applied to assess the economic effects of a wide range of issues, such as tax reforms, trade liberalization, energy policy, the economic effects of climate change impacts, and also the impacts of disasters. A CGE model is a system of equations which describes the behaviour of the representative economic agents, household and firm, the structure of markets and institutions, and the relations between them. In synthesis, in the model consumers maximize utility and firms maximize profit. The primary factors, i.e. land, capital, labour and natural resources, are owned by the household and are fixed in supply. The equilibrium in the market system is achieved when the demands of buyers match the supplies of sellers at prevailing prices in every market simultaneously. CGE trade models have a Walrasian structures where money is neutral, factors are fully employed, and the markets are perfectly competitive. Compared to other type of models (e.g. Input/Output models or econometric models) this 'dynamic' structure of the economy has advantages and limitation for disaster's impact assessments. In particular, CGE models can describe the systemic economic channels through impacts propagate within and between the economies affected and non-affected (Moffatt and Hanley 2001; Rose 2004; Bosello et al 2006; Okuyama 2007; Hallegatte 2008; Bosello et al 2012; Liang et al 2014). Moreover CGE models are well suited to assess the impacts on the supply side, allowing for flexibilities in the economic system such as substitution and mobility (Hallegatte 2008). CGE models flexibility capture the feedback effects from the macro-economic context on the "markets" initially concerned (Rose 2004). Nonetheless, CGE models have several limitations. They assume perfect markets and they are not able to capture non-market values (Pauw, K. et al 2011). Global CGE models generally have "coarse" investigation units, usually the countries. This may allow analysis of aggregated events or trends, but makes local analyses particularly challenging, especially for small to medium disasters. Our regionally calibrated model (R-CGE) overcome this problem, providing an economic analysis at higher resolution.

The outcomes of our this paper provide EAOL per region and Italy as a whole, obtained from the 12 climate experiments of the ENSEMBLES (EU FP6) project (Van der Linden and Mitchell 2009). The experiments cover a period from 1961 till 2100, based on 4 GCMs and 7 RCMs, with an horizontal resolution of 25km. The hydrological component is based on LISFLOOD results (Feyen et al 2007; Feyen et al 2008; Van Der Knijff et al 2010; Rojas et al 2013) The economy and society is static over time, that is we do not consider socio-economic changes. This allow us to distinguish climate change effects only, which are estimated under two risk mitigation scenarios: with and without adaptation. The avoided losses of adaptation represent the potential benefits of risk mitigation policies.

Concluding, in the following section (Section 2) we provide further details on the conceptual framework and the methodology, we describe the sample data and the model. Following, in Section 3 and 4, results are presented and discussed. Section 5 concludes the paper providing a critical review of the outcomes, in the broader context of flood impact assessment and risk mitigation policies.

4.2. Methodology

4.2.1. Terminology

The terminology used in the literature related to the impacts of natural disasters is various. In general impacts are divided between tangible and intangible (Merz et al 2010a; Meyer et al 2013). Tangible are the impacts that can be measured in monetary terms (Smith and Ward 1998), while intangible are the impacts that are difficult to translate into monetary values[6]. In part of the literature tangible impacts are categorized into direct and indirect (Parker et al 1987; Smith and

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[6] In this paper we only consider tangible impacts, neglecting the intangibles, which require a different investigation approach other than the one considered in this work.

Ward 1998; NRS 1999; Merz et al 2010b; Balbi et al 2011; Meyer et al 2013). Direct impacts are defined as losses affecting humans, assets, properties, and any other asset and good in the areas that had physical contact with the flood (Merz et al 2010b). For example the residential damages to any building in the flooded area, the goods that are destroyed inside the buildings, the cars that are damaged or the infrastructures that are washed away.

A more recent framework developed by Meyer et al (2013) distinguishes the economic losses between direct costs, which are damages to properties in the area of the hazard, business interruption costs, which occur to business directly affected by the hazard, often referred as primary indirect damages because they are induced by the interruption of business activities, and indirect costs, which occurs outside (and inside[7]) and the flooded area, and are caused by direct costs and/or business interruption costs (Przyluski and Hallegatte 2011).

Despite the clarity of these definitions, from an economic perspective the distinction between direct and indirect costs is difficult to put into practice (Rose 2004). Instead, the division between stock and flows appears to be more suited for the assessment of disaster's economic losses (Rose 2004), where the stock is the quantity of physical capital at a single point time, and the flows are the output of stock over time.

Combining the different approaches is not an easy task. However some authors tried to legitimate this combination. The (NRC 2011) defines the impact to the stock as the property damage at one given point, and the impact to the flows as the loss of production of goods and services until recovery is completed. The (NRC 2012) affirms that stock and flow losses can be both direct and indirect. Direct stock losses are the ones occurring directly, for example, to the buildings. Indirect stock losses are the damage to the stock which occurs indirectly, for example, the fires generated by the rupture of gas pipes which were damaged by the earthquake (NRC 2012). On the other side, direct flow losses are the ones occurring in the affected area to business which suffer disruptions to their activities. Because of the ripple effect to the supply chain, indirect flow losses can occur to other businesses outside the impacted area. In a more conceived manner (UNISDR 2013) directly relates stock losses to direct impacts and flow losses (i.e. business interruption[8] and wider impacts[9]) to indirect impacts. A similar classification, even if not clearly related to the duality direct-indirect, is provided by (Hallegatte 2014a), which refers to asset losses as the stock of assets that is destroyed, and to output losses as the reduction in the income flow (Rose et al 2007). In this case output losses

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[7] This is partially in contradiction with (Merz et al 2010a), which considers indirect as losses affecting entities outside the flooded area.

[8] Business interruptions are a consequence of direct losses or impacts to the supply chain of businesses, which negatively influence clients, partners and suppliers. The interruption causes the reduction of business outputs, revenues and profitability (UNISDR 2013).

[9] Wider impacts refers to different consequences like labour shortage, negative effects on business reputation, loss of market share, influences on future insurance, worsening relations with clients and suppliers, etc. (UNISDR 2013).

are caused by several effects which overlap one with the other, i.e. production losses due by damaged assets, supply-chain disruptions, macro-economic effects, long and short economic consequences to growth and economic incentives due to reconstruction (Hallegatte 2014a).

Here, for simplicity and clearness, we use the latter described terminology. As in (Hallegatte 2014a) we divide losses between assets and outputs. We focus our analysis on output losses and we use a classic economic indicator, the Gross Domestic Product (GRP) to capture this category of losses. We acknowledge the fact that GRP, like Gross Domestic Product (GDP), is a poor indicator for output losses (Hallegatte 2014a). Indeed, GDP does not capture non-market and household production. It does not measure wealth because it does not include the stock of assets but only the flows. It does not represents inequalities and heterogeneity within a region. But, on the contrary of GDP which has a spatial scale problem (the national scale is too large for average-scale natural hazard), GRP is more suited to the specific spatial scale of fluvial floods (normally local or regional). Moreover, GRP has already been used for the economic assessments of flood losses (Jonkhoff 2009; Pfurtscheller 2014) and, to our knowledge, it is one of the most easily available economic indicators.

4.2.2. General framework

Our model is conceptually described in Figure 14. Going forward (from left to right) we proceed as follows: (1) hazard: flood extension maps per 5 time steps and 8 return periods (for a total of 40 simulations) are deduced from 12 climate models (described in Section 4.2.3.1) and the LISFLOOD hydrological model (described in Section 4.2.3.2); (2) exposure: we match Corine Land Cover (CLC) 2000 classes with the selected economic sectors (14 sectors described in Section 4.2.3.3**Errore. L'origine riferimento non è stata trovata.**). The result is a “spatial” economy, that is, economic activities are spatially distributed over the territory under investigation; (3) impact: the overlay of hazard and exposure provides the impact, which we translate into a reduction in the capacity of producing goods and services per sector per NUTS2 region (described in Section 4.2.4.2); (4) output loss: we “shock” the economic model (R-CGE) with the previously calculated impact per NUTS2 region and we obtain an expected loss (or gain) of GRP per each event with a specific return period and over the five time steps (for a total of 40 events); (5) EAOL: from the expected losses we designed the probability loss curves (section 4.2.5). We set homogenous and heterogeneous (2 scenarios described in Section 4.2.5.1) flood protection standards and we calculate the Expected Annual Output Loss (EAOL) per NUTS2 regions per time step up to the 2080s.

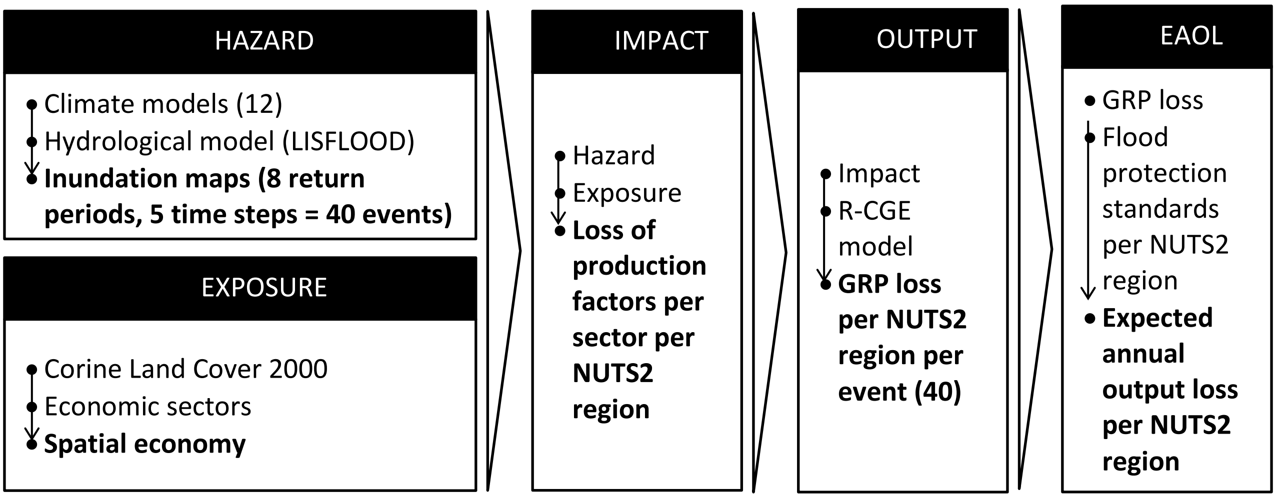

Figure 14: conceptual map of the model to estimate output losses and expected annual output losses (EAOL).

4.2.3. Inputs for the hazard and the exposure components

Flood input data for this work are provided by the Joint Research Center (JRC) within the EU Project ENHANCE. With similar purposes Feyen et al. (2012) and Rojas et al. (2013) already used the dataset to estimate asset losses (the so called direct impacts). For more details about the dataset (i.e. climate models, hydrological models, land use and population data, and the assessment of asset losses) we refer the reader to Sections 4.2.3.1, 4.2.3.2 and to Feyen et al. (2012) and Rojas et al. (2013).

4.2.3.1. Climate simulation

We analyze the results of 12 climate experiments (Table …. in Appendix) obtained from the ENSEMBLES EU project (Van der Linden and Mitchell 2009). The climate experiments cover the period 1961-2100 and are based on 4 GCMs and 7 RCMs. The outputs have horizontal resolution of 25km, daily temporal steps and are forced on the SRES-A1B scenario (Nakicenovic and Swart 2000). We use the climate data to "run" the hydrological simulation with the LISFLOOD model (Van Der Knijff et al 2010).

4.2.3.2. Hydrological simulation

River discharge simulations are obtained with the LISFLOOD model, which is a GIS-based model where "processes like infiltration, water consumption by plants, snowmelt, freezing of soils, surface runoff and groundwater storage" are taken into account at 5km grid resolution and daily steps (Rojas et al. 2013). For a more detailed description of the model we refer the reader to (Feyen et al 2007; Feyen et al 2008; Van Der Knijff et al 2010). Our work makes use of the outputs of LISFLOOD for 5 time steps (ctrl, 2000, 2020, 2050, 2080) of 30 years duration each (1961-1990, 1981-2010, 2011-2040, 2041-2070, 2071-2100), over 8 flood return periods (2, 5, 10, 20, 50, 100, 250, 500). The return periods are derived from fitted Gumbel distributions to the maximum annual discharge for each river. For more details on the flood hazard assessment we refer the reader to (Rojas et al 2012).

4.2.3.3. Exposed assets

The territory of our analysis is spatially represented, in terms of land use, by Corine Land Cover (CLC) 2000 (EEA 2002) . CORINE has 44 land cover classes and an horizontal resolution of 100m (EEA 2002).

In order to assess the impact of a flood event to the economic system, we define a relation between the land use classes of CLC2000 and the economic sector of our R-CGE model (Table 5).

Table 12: our CGE model sectors

CGE sector	Description
AirTrans	Air transport
Construction	Construction
Crops	Agriculture: wheat, cereal grains nec, paddy rice
Fishing	Fishing
Forestry	Forestry
HeavyManif	Heavy manifacturing: paper products, publishing, petroleum, coal products, chemical, rubber, plastic products, mineral products nec, ferrous metals, metals nec, metal products, motor vehicles and parts, transport equipment nec
Light Manif	Light manifacturing: textiles, wearing apparel, leather products, wood products, electronic equipment, machinery and equipment nec, manufactures nec
Livestock	Livestock: bovine cattle, sheep and goats, horses, animal products nec, raw milk, wool, silk-worm cocoons
Minerals	Minerals: coal, oil, gas
OtherCrops	Other crops: sugar cane, sugar beet, plant-based fibers, vegetables, fruit, nuts, oil seeds
ProcFood	Processed food: bovine meat products, meat products nec, vegetable oils and fats, dairy products, processed rice, sugar, food products nec, beverages and tobacco products
Services	Services: communication, financial services, insurance, business services, recreational and other services, public administration, defense, education, health, dwellings, trade
Transport	Trasport: transport nec, water transport
Utilities	Utilities: electricity, gas manufacture, distribution, water

The matching of land cover classes and economic activities is performed through a qualitative analysis of CLC2000 classes description (ref. website) and the economic sectors provided by GTAP (ref. website). The selection is made on authors' expert judgment. For example, we assume that the crop sector (i.e. wheat, cereal grains, paddy rice) corresponds to the area defined by CLC2000 as permanently irrigated land, non-irrigated arable land, and rice field. Also, we assume for example that the *services* are locate in constructed areas, i.e. continuous urban fabric, discontinuous urban fabric, industrial or commercial units, along roads and railways, and in leisure and touristic areas such as the green urban areas, sport and leisure facilities, and along beaches. Our aggregation allows the same land use class to be associated with more than one sector (e.g. permanently irrigated land with crops and other crops) and one sector to be associated with more than one land use class, as described before for the services. Table 13 shows these relations.

Table 13: association of the Corine Land Cover (2000) classes to the 14 CGE economic sectors of the CGE model. The remaining CLCs classes, which are not mentioned in the table, are not considered.

CLC code	CLC class	CGE sector
111	Continuous urban fabric	Services
112	Discontinuous urban fabric	Services
121	Industrial or commercial units	ProcFood HeavyManif Light Manif Utilities Services
122	Road and rail networks and associated land	Utilities Services Transport
123	Port areas	Transport Utilities
124	Airports	AirTrans
131	Mineral extraction sites	Minerals
133	Construction sites	Construction
141	Green urban areas	Services
142	Sport and leisure facilities	Services
211	Non-irrigated arable land	Crops
212	Permanently irrigated land	Crops OtherCrops
213	Rice fields	Crops
221	Vineyards	OtherCrops
222	Fruit trees and berry plantations	OtherCrops
223	Olive groves	OtherCrops
231	Pastures	Livestock
241	Annual crops associated with permanent crops	OtherCrops
242	Complex cultivation patterns	OtherCrops
243	Land principally occupied by agriculture, with significant areas of natural vegetation	Crops
244	Agro-forestry areas	OtherCrops Forestry
311	Broad-leaved forest	Forestry
312	Coniferous forest	Forestry
313	Mixed forest	Forestry
331	Beaches, dunes, sands	Services
511	Water courses	Fishing
512	Water bodies	Fishing
521	Coastal lagoons	Fishing
522	Estuaries	Fishing

The matching provide a sort of “spatial”[10] economy, where economic activities are distributed across the Italian territory.

4.2.4. Estimation of output losses

We use a regionally calibrated CGE model to assess the output losses of flood risk. We apply a conceptually similar methodology to the one used in (Carrera et al 2015), with few modifications, including a CGE model calibrated at NUTS2 regional level.

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[10] Describe the classical definition of spatial economy (or geographical economy) and explain why we use vertical commas.

In general a CGE model is a system of equations which describes the behaviour of the economic agents (representative household and firm), the structure of the markets and the institutions, and the links between them. In the model mechanisms, consumers maximize utility subject to an individual budget constrain and firms maximize profit choosing the amount of inputs for their production. Primary factors of production, such as land, capital, labour and natural resources, are owned by the household and are fixed in supply. The equilibrium in the market system is achieved when the demands of buyers match the supplies of sellers at prevailing prices in every market simultaneously. Global CGE trade models, such as the one used for this work, which is based on GTAP7 (Global Trade Analysis Project, reference year 2004) (Narayanan and Walmsley 2008) have a Walrasian structure. Money is neutral, factors are fully employed, and the markets are perfectly competitive. In addition, macro-economic closure is neoclassical as investments are driven by savings. Trade balance is determined endogenously. CGE model parameterization derives from a calibration procedure. That is, key behavioural parameters replicate the observed demand and supply relations in a given reference year. We followed the same procedure for the specification of the relations of our regionally calibrated CGE model (see Section 4.2.4.1 and Appendix for the description of CES (constant elasticity of substitution) and CET (Constant Elasticity of Transformation) functions).

Our R-CGE model rely on the following assumptions: (a) the shock (i.e. the flood) is enforced to the one year point of the disaster occurrence and does not influence precedent or subsequent years; (b) output losses are generated by the disruption of the production, which is a consequence of the loss of assets; (c) the flood events are independent Bernoulli random variables each with a probability of occurrence given by the return period; (d) subsidies and post-disaster reconstruction are not accounted for in the economic model; (e) inventories are not considered; (f) the reduction in factors productivity is recovered within one year. Therefore, the time scale of our analysis is one year and the model is static. Each single 'shock' to the economic system (in our case to the productivity of primary factors of production such as capital, land, labour) translates into an yearly loss of output; g) we consider climate change effects only, disregarding of socio-economic changes.

4.2.4.1. The regional calibration of the global CGE model

Our sub-national CGE model is based on GTAP 7 (Global Trade Analysis Project, reference year 2004). For Italy, we downscale the country based model to regional level using three panel data: (1) the GTAP 7 database (Narayanan and Walmsley 2008) which of consists of 57 sectors and 113 countries or groups of countries (2004); (2) the regional panel data of ISTAT (*Italian National Statistical Institute*) from the same year, which provides information on value added, labour and land for the 20 Italian regions and 40 economic sectors; (3) ISTAT bilateral flows of carried goods (in tons) by mode of transportation (truck, rail, water and air) for the 20 Italian regions. We follow a three steps procedure: (a) we match the 40 ISTAT sectors with the 24 GTAP sectors chosen in our aggregation and reported in *Table 5*. We distribute the Italian value added and primary factors in GTAP across the 20 Italian regions using the shares of ISTAT for value added, labour and land. Capital is computed as the difference between value added and labour. For the sectors that use natural resources we take the regional share of value added in those sector as a proxy; (b) we use the shares obtained from ISTAT transport data to split the sectorial GTAP Italian production between domestic regional demand and bilateral trade flows across Italian regions; (c) we adjust the bilateral trade flows across Italian regions to make them consistent with the ISTAT data on the economic production. For additional details on the calibration of the model we refer the reader to (Standardi et al 2014).

These modelling improvements requires the modification of the theoretical structure of the model in order to incorporate the possibility of an increasing spatial mobility in both factors and goods market at regional level, because both goods and factors usually move easier within the country than between countries. For example, in GTAP the factor endowments cannot move outside the country they belong. This makes sense in a national context but it is unlikely to happen at the regional level. Although the presence of friction it is evident that workers and capital can reallocate in other regions after an economic shock. Moreover, regarding the product substitution from the demand side, in a standard CGE model the Armington assumption (Armington 1969) prevents unrealistic specialization phenomenon and trade overflows from warping the results of the model. The values of the Armington elasticity are set by econometric estimations, which are carried out at the national level. Because of the empirical evidence about the fact that trade within a country is bigger than trade between countries given the same distance, the so-called border effect (McCallum 1995), these Armington elasticities are recalibrated at regional level and the demand structure modify to consider the increased product substitution inside the borders.

We consider a recovery scenario were factor endowments can move outside the region they belong and products are closer substitutes within regions. We introduce capital and labour mobility within Italy (endogenous factor supply at regional level) through a CET (constant elasticity of transformation) function (see Appendix for additional details). As a result workers and capital can move outside the region they belong after a shock in the economic system. We also increase the values of the Armington elasticity for the regions to take into account the fact that products are closer substitutes within the country than across countries (see Appendix for additional details).

4.2.4.2. Impact: the “shock” to the economy and the expected output loss

The impact is given by the combination of hazard and exposure, associated with a specific probability of occurrence, which is derived from the JRC's dataset described in Section 4.2.3. For each time step and each flood return periods (for a total of 40 simulations) we calculate the percentage of flooded area per economic sector (as described in Section 4.2.3.3) per NUTS2 region.

The "shock" to the economy is simulated by reducing (in percentage) the primary factors' (capital, land and labour) productivity, which are exogenous factors of the R-CGE model. The percentage of reduction corresponds to the percentage of impact. For instance, if 10 percent of industrial areas in the Lombardy regions are flooded, we assume that 10 percent of the capital of the heavy manufacturing capital sector is unusable for a certain period of time, which we assume being one year. The same applies to labour (theoretically heavy manufacturing does not use land).

Equation 1 describes how we estimate the impact:

$$(1)\quad I_{S,R}\,[\%] = \frac{AA_{S,R}}{TA_{S,R}}$$

where I is the impact (in %), AA is the affected area (in Km2), TA is the total area (in Km2), S is the economic sector (Table 5) and R is the NUTS2 region.

The affected area (AA) is a weighted area based on water depth (equation 2). To account for the influence of water depth on the impact, we assumed that the higher is the water level, the higher is the productivity loss, following a square root relation (Figure 15). This assumption is based on three principles: a) higher water depth causes larger asset losses as described by stage-damage functions (De Moel and Aerts 2011; De Moel et al 2012; Jongman et al 2012a; Saint-Geours et al 2014); b) larger asset losses ideally require longer recovery periods; c) in general, the duration of the retreat of water after flooding is dependent from its water depth. The inclusion of a water depth coefficient is based on similar approaches in the assessment of asset losses (Feyen et al 2012; Jongman et al 2012a; Rojas et al 2013). The relation between water depth and the level of assets damage is characterised by an high level of uncertainty, particularly in Italy, where nation-wide flood depth-damage function are not available. The lack of knowledge in the relation between water depth and loss of production is even more pronounced than the one related to asset losses (De Moel and Aerts 2011; Jongman et al 2012a). However we acknowledge the importance of considering this relation. Thus, based on the literature on flood damage functions (De Moel and Aerts 2011; De Moel et al 2012; Jongman et al 2012a; Saint-Geours et al 2014) and on author's expert judgment, we assume a square root curve relation. The result is represented in Figure 15, and the curve has been used to estimate the level of impact per sector, following equation 2.

$$(2)\ AA_{S,R} = \sum_{i=1}^{n} FC_{S,R\,i} \times c_i$$

where FC is the flooded cell (100x100m) i, c is the damage factor applied to each FCi based on Figure 15 and n is the number of cells belonging to the NUTS2 region R and the sector S.

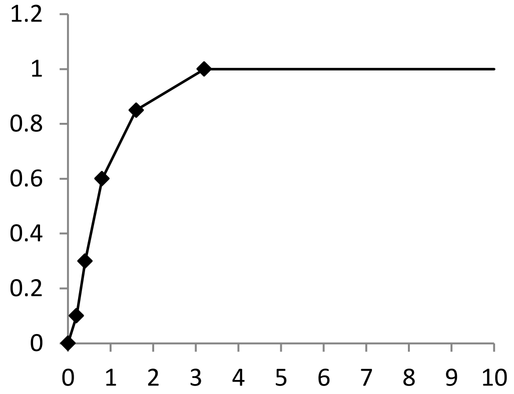

Figure 15: the water depth-productivity loss curve considered in this study.

The recovery period for a business is characterize by multiple uncertainties, depending on the type of business, its location, the possibility for relocating production and activities, the elevation of the water level, the duration of water staying, etc. Given this level of uncertainty we assumed the businesses recovery period being one year. However, we acknowledge the fact that our assumption could lead to a poorly accurate estimation of output losses, which could be over or under estimated depending on the type of business and its location.

Using the R-CGE model, for each climate experiment, flood return period and time period (for a total 960 simulations) we calculate the specific expected output loss (or gain) per NUTS2 region, in terms of percentage of GRP change and percentage of production per sector change.

4.2.5. Loss probability curves: the expected annual output loss (EAOL)

In our model the flood events (characterized by a specific return period) are assumed independent Bernoulli random variables, each with a probability function defined as:

P(Ei happening) = pi

P(Ei not happening) = (1-pi)

where E is flood event and p is the annual probability of occurrence (calculated as 1 divided by the return period).

If the flood does not occur the loss is zero. If the flood occurs the expected loss E(L) for a given year is:

Ei(L) = piLi

where in our model the E(L) is the expected output loss.

For a set of events each with a probability pi and an associated loss Li, the EAOL is calculated as the integral of the damage curve truncated at the specific flood protection standard, which is defined as the minimum statistical probability discharge that leads to flooding. We calculate the integral with the trapezoidal rule:

$$EAOL = \frac{1}{2}\sum_{i=FPS}^{10,000}\left(\frac{1}{x_1} - \frac{1}{x_{i+1}}\right)(E(L)_{i+1} + E(L)_i)$$

Where i is the time between two events with expected loss E(L), and FPS is the flood protection standard. We calculate the EAOL from an event with a return period of 1 per 1.5 years to an event (interpolated) with a return period of 1 per 10,000 years.

4.2.5.1. Flood protection standards

EAOLs are estimated under two flood protection standards (FPS) scenarios: one homogeneous across al NUTS2 regions and one heterogeneous. The homogeneous FPS scenario considers different protection standards, amongst the most common in Europe (Jongman et al 2014), i.e. 1 per 20, 50, 100 and 250 years across all regions. The heterogeneous FPS scenario is based on the estimations provided in Jongman et al (2014). FPSs were estimated for each European river basin following three steps based on the combination of three criteria: the average potential damage of assets per m^2 (i.e., higher the potential, higher the protection level), literature studies and points of known flood protection. For further information about the methodology used and the results, we refer the reader to Jongman et al (2014).

In order to be consistent with the scale of analysis of the R-CGE model, we calculate the average standard protection level per NUTS2 region (Table 14) according to Jongman's results. In general the standards of protection are higher in the North and the Center, lower in the South and the Islands. This is probably due to a variety of factors, including socio-economic characteristics, the shape of the Italian peninsula, the typical orography of the territory, and the class of rivers of the Apennines of the Center and South, which, omitting exceptions like the Arno, Tevere, Volturno and few others, have stream-type regimes, which may lead to lower protection standards.

Table 14: Average-base ensemble flood protection standard (1 per years) per NUTS2 regions of Italy, and Italy as a whole (average). Own elaboration on Jongman et al., 2014.

NUTS code	Name	Prot. Std. 1980s
ITC1	Piedmont	137
ITC2	Aosta Valley	131
ITC3	Liguria	147
ITC4	Lombardy	156
ITD1 - ITD2	Tren. Alto Adige	157
ITD3	Veneto	161

ITD4	Friuli Ven. Giulia	89
ITD5	Emilia Romagna	151
ITE1	Tuscany	117
ITE2	Umbria	149
ITE3	Marche	105
ITE4	Lazio	116
ITF1	Abruzzi	88
ITF2	Molise	37
ITF3	Campania	56
ITF4	Apulia	27
ITF5	Basilicata	22
ITF6	Calabria	39
ITG1	Sicily	27
ITG2	Sardinia	36
IT	Average ITALY	97

For both homogeneous and heterogeneous FPDs scenarios, EAOLs are calculated setting to zero all expected losses below the specific regional FPS.

4.2.5.2. Risk management scenarios: climate change adaptation

In this work we investigated two risk management scenarios: *adaptation* and *no adaption*. In the first scenario, named *adaptation*, we assume FPSs constant over time. That is, the protection standards are assumed to be maintained at the same failure probability, under changing climate conditions. For example, if in the 1980s the protection standard is 1 per 100 years, in the 2080s the protection standard is still 1 per 100 year.

In the second scenario, *no-adaptation*, FPSs change over time according to the modification of river discharge due to climate change. For example, if in 1980 the FPS is 1 per 100 years, in 2080 the FPS is modified according the return period associated to the same river discharge, for example, 86 years. This means that flood protection standards are not upgraded to changing river discharge conditions. It is also possible (in some regions of the South) that flood river discharge decreases. As a consequence current FPSs increases in the future (in terms of return period) (e.g. from an event of 1 per 30 years to an event of 1 per 50 years). In this case the EAOL is calculating breaking off the integral of the probability loss curve with the new FPS. That is, protection standards are never physically downgraded but the probability of flooding decreases due to climate change. The two scenarios are estimated assuming an homogenous FPS at 1 per 100 years (which is a medium probability event according to the EU Flood Directive), and heterogeneous FPSs across NUTS2 regions (Table 14).

We calculate the EAOL for the two risk management scenarios, for the 12 climate experiments and the average-based ensemble. The difference between the two represents an estimation of the benefits (avoided losses) of adaptation, where for adaptation we refer to flood protection only.

4.3. Results

4.3.1. Output losses per region

For a constant flood protection standard of 1 per 100 years across all regions, under a medium-high emission scenario (A1B), the ensemble-based average estimate of output losses in Italy increases over time. Due to the effects of climate change, total output losses raise from 188 million Euro in the 2000s to 231 million (constant 2004 prices undiscounted) in 2080s (ensemble mean). The 23 percent of increase is lower than the one reported by (Rojas et al 2013) in the work on EU asset losses using the same input dataset, but is still consistent. This difference is probably due to the vulnerability level to flooding of the flows versus the stock of assets, which in Europe is predominantly residential (ref.). In our simulation the flows appears less susceptible to changes in river discharge.

The variability across the 12 climate experiments used to force the hydrological model LISFLOOD is represented in Figure 16. The upper end of the range is obtained from the ETHZ-CLM-HadCM3 experiment (see ref. to table in Appendix) while the lower end of the interval is obtained from the SMHI-RCA-ECHAM5, except for the 2050s when the lower bond is given by the SMHI-RCA-ECHAM5 simulation .

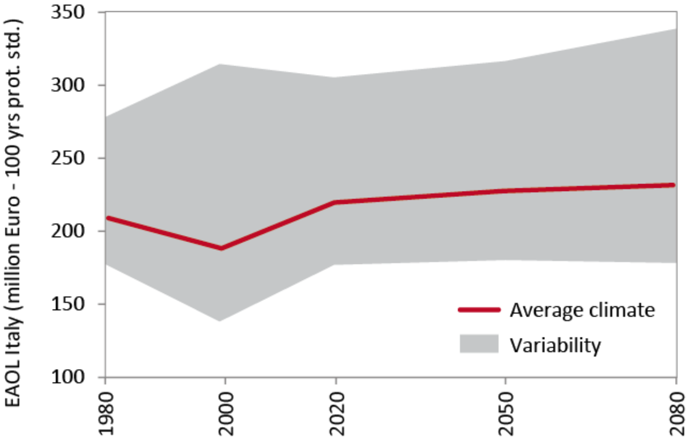

Figure 16: Expected annual output loss for Italy (in million Euro, constant 2004 prices): ensemble-based average and 12 climate simulation variability under the A1B emission scenario for a 1 per 100 flood protection standard.

Losses are distributed heterogeneously across the Italian territory. Considering a constant flood protection standard of 1 per 100 years across all regions, the distribution of losses is largely dominated by the high values of Lombardy, followed by Veneto, Tuscany, Emilia-Romagna and Piedmont. Excluding Lazio, the largest losses are reported unsurprisingly in the largest economies of the North (and Centre). Climate change does not influence the regional out losses homogeneously. The highest losses increase from the 2000s to the 2080s is projected in the Aosta Valley (41 percent).

Some regions experience increases in the same order of magnitude: Lombardy 32 percent, Emilia-Romagna 36 percent, Abruzzo 37 percent. In other regions the increase is less pronounced (e.g. Piedmont 14 percent, Veneto 7 percent, Calabria 14 percent and Sardinia 11 percent). It is worth noting that the regions Apulia, Basilicata and Campania show net benefits in response to probabilistic flood risk. Apulia and Basilicata show net benefit from flood risk in all time periods, while Campania experience losses in the control period (1980s) only.

Table 15: expected annual output losses per regions and Italy as a whole: ensemble-based average (in million Euro, constant 2004 prices) for the flood protection standards of 1 per 2, 50, 100, 250 years. Negative values represent gains.

NUTS	Name	Control				2000s				2020s				2050s				2080s			
		20y	50y	100y	250y	20y	50y	100y	250y	20y	50y	100y	250y	20y	50y	100y	250y	20y	50y	100y	250y
ITC1	Piedmont	87.0	38.8	20.1	8.3	86.2	35.8	17.0	5.1	88.2	39.2	20.1	8.2	84.1	37.6	19.4	8.0	85.9	37.8	19.4	7.8
ITC2	Aosta Valley	9.1	4.2	2.2	0.9	9.3	3.9	1.9	0.6	9.9	4.5	2.4	1.0	10.9	5.0	2.6	1.1	11.7	5.3	2.7	1.1
ITC3	Liguria	34.4	15.3	7.9	3.2	36.4	15.1	7.2	2.3	35.5	15.8	8.2	3.4	37.7	16.9	8.7	3.6	40.0	18.0	9.3	3.8
ITC4	Lombardy	174.0	80.7	42.6	17.9	183.0	79.8	39.3	12.6	188.3	87.7	46.3	19.5	199.8	93.7	49.6	20.8	212.0	98.2	51.9	21.5
ITD1-2	Tren. A.A.	51.2	22.8	11.8	4.8	52.4	21.6	10.3	3.1	54.6	24.2	12.5	5.1	55.8	24.9	12.8	5.2	59.0	26.0	13.4	5.4
ITD3	Veneto	149.2	67.0	34.9	14.4	170.4	71.7	34.3	10.5	164.5	74.0	38.2	15.7	154.3	70.2	36.6	15.1	159.8	71.8	37.0	14.9
ITD4	Friuli V.G.	8.6	4.8	2.8	1.3	11.6	6.1	3.3	1.2	11.7	6.6	3.8	1.8	13.5	7.6	4.5	2.1	12.3	6.9	4.0	1.8
ITD5	Emilia-Rom.	85.5	39.0	20.5	8.5	85.5	36.2	17.5	5.4	91.8	41.9	21.9	9.2	95.7	44.3	23.4	9.8	99.2	45.6	24.0	9.8
ITE1	Tuscany	101.8	46.9	24.8	10.4	105.9	45.4	22.1	7.0	106.4	48.8	25.5	10.7	114.3	53.2	28.3	11.9	114.4	52.9	27.8	11.5
ITE2	Umbria	16.6	7.2	3.7	1.5	16.3	6.6	3.1	0.9	17.0	7.4	3.7	1.5	16.7	7.3	3.7	1.5	16.6	7.2	3.6	1.5
ITE3	Marche	31.0	14.2	7.5	3.1	33.8	14.5	7.1	2.3	33.1	15.1	7.9	3.3	35.0	16.2	8.6	3.6	36.6	16.9	8.9	3.7
ITE4	Lazio	30.0	12.7	6.3	2.5	26.9	10.3	4.7	1.4	25.6	10.6	5.3	2.1	23.6	9.7	4.8	1.9	21.5	8.8	4.3	1.6
ITF1	Abruzzo	28.8	13.7	7.3	3.1	32.5	14.5	7.3	2.5	32.1	15.4	8.3	3.5	37.2	17.9	9.7	4.2	38.8	18.6	10.0	4.2
ITF2	Molise	4.5	2.0	1.0	0.4	4.4	1.8	0.9	0.3	4.5	2.0	1.0	0.4	4.4	2.0	1.0	0.4	4.4	1.9	1.0	0.4
ITF3	Campania	0.7	0.9	0.6	0.3	-4.8	-1.5	-0.5	-0.1	-4.2	-1.5	-0.7	-0.2	-2.7	-0.9	-0.3	-0.1	-2.4	-0.8	-0.3	-0.1
ITF4	Apulia	-10.1	-4.6	-2.4	-1.0	-10.7	-4.6	-2.2	-0.7	-10.6	-4.9	-2.6	-1.1	-11.1	-5.1	-2.7	-1.1	-10.9	-4.9	-2.6	-1.0
ITF5	Basilicata	-0.1	-0.1	0.0	0.0	-0.2	-0.1	-0.1	0.0	-0.3	-0.1	-0.1	0.0	-0.3	-0.1	-0.1	0.0	-0.3	-0.1	-0.1	0.0
ITF6	Calabria	8.9	4.1	2.2	0.9	9.0	4.0	1.9	0.6	9.5	4.4	2.3	1.0	9.3	4.4	2.3	1.0	9.2	4.2	2.2	0.9
ITG1	Sicily	37.8	17.1	8.9	3.7	37.7	16.1	7.8	2.5	39.0	17.7	9.2	3.8	36.5	16.7	8.7	3.6	38.7	17.6	9.1	3.7
ITG2	Sardinia	29.2	12.6	6.4	2.6	28.1	11.3	5.3	1.6	28.7	12.4	6.3	2.5	26.8	11.7	5.9	2.4	26.7	11.7	5.9	2.3
IT	ITALY	878.1	399.4	209.1	86.8	913.7	388.5	188.4	59.2	925.2	421.2	219.7	91.3	941.7	432.9	227.5	94.8	973.1	443.5	231.7	94.8

Figure 17 shows the ensemble-based EAOL estimates at regional level, with consideration to the flood protection standards estimated by (Jongman et al 2014) (Table 14). In Italy as a whole the EAOL is projected to increase from 164 million Euro in the 2000s to 204 million Euro (constant 2004 prices) in the 2080s. The 25 percent increase is in line with the results obtained using an homogeneous protection level across all regions. However, because of heterogeneity of protection, we observe a redistribution of output losses towards some regions of the South, which experience the lowest protection standards (up to 1 per 22 years). Although the North is still predominant recording 50 percent of total national losses, the Islands 27 percent, the Center 19 percent and 4 percent in the South, there is different distribution of losses compared to the homogenous protection, where the North was recoding almost 70 percent of losses and the Islands 7 percent only.

In the 2000s Sicily is located at the higher end of the distribution, with 29 million Euro (18 percent of national losses), followed by Lombardy (around 24 million Euro, 14 percent of national losses), Veneto with around 20 million Euro (12 percent of national losses) and Tuscany with around 19 million Euro (11 percent of national losses). In the same time period, Apulia, Campania and Basilicata show output gains due the redistribution of production and demand, with 8 million Euro, 1 million Euro and less than 1 million Euro respectively. Climate change produce a further redistribution of losses, which is projected in the 2080s output. Generally, the northern regions are more affected from climate change. The share of losses grows in the North from 50 to 53 percent of the national losses, while the Center and the South hold almost constant, and the Islands reduce their share of losses from 27 to 23 percent of national losses. In the 2080s Lombardy is projected to be the region with the highest EAOL (34 million Euro, 17 percent of national losses, 44 percent increase from the 2000s to the 2080s), while Sicily is projected to increase with a slower pace (7 percent). The highest increases of EAOL due to climate change are projected in Emilia-Romagna (49 percent by 2080s), Aosta Valley (48 percent by 2080s) and Trentino Alto Adige (42 percent by 2080s), in addition to Lombardy, already mentioned. In general the increase of losses is lower in South, where the percentage does not exceed 7 percent. In the South the only exception is Abruzzi where climate change induce an additional 35 percent by 2080s to the 2000s EAOL. This is probably due to its higher latitude compare to the other southern regions.

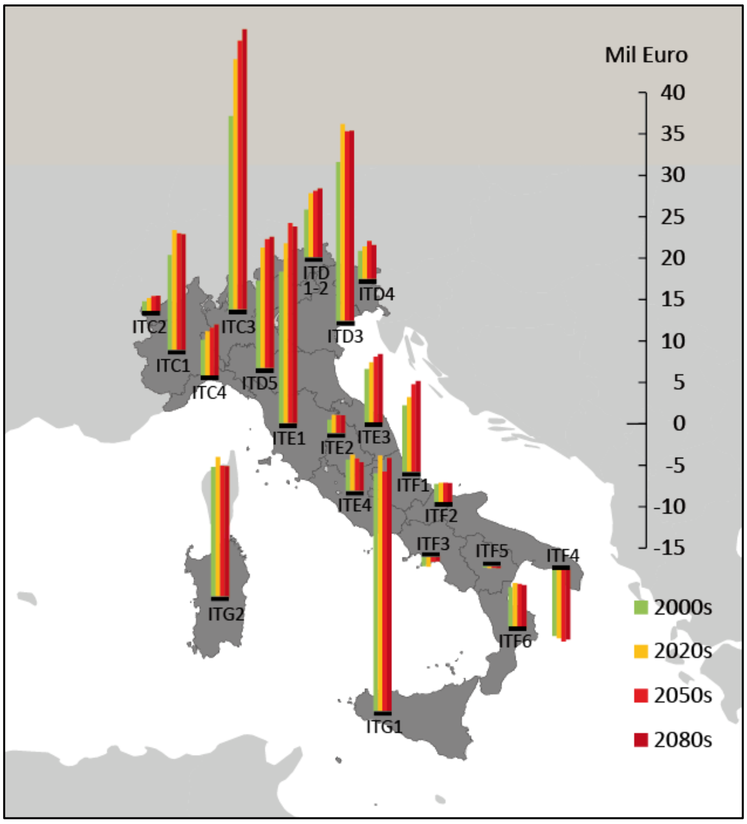

Figure 17: Expected annual output losses per region: ensemble-based average (in million Euro, constant 2004 prices) for the flood protection standards based on Jongman et al. 2014. Negative values represent gains (ITF3, ITF4, ITF5).

In order to highlight the relative effect of flood risk to regional economies, Figure 18 shows the ensemble-based average estimates of output losses (in percentage of GRP) per region and the variability given by the 12 climate simulations. Compared to GRP, all regions suffer EAOL lower than 0.1%. In relative terms the Aosta Valley is the one experiencing the highest EOAL. The average-based ensemble impact is 0.06 percent in the 2000s, increasing to more than 0.08% in 2080s. Trentino Alto Adige shows similar EAOL percentages for the ensemble-based average, 0.04 percent in the 2000s increasing to 0.05 percent by the 2080s. In all the other regions the EAOL for the ensemble-based average ranges between 0.01 and 0.04 percent, generally with an increasing trend over time, due to climate change. As before it worth to highlight that Campania, Calabria and particularly Apulia report a net benefit from flood risk, although the percentage of expected annual output gain is lower than the losses reported by the other regions.

A large range of variability arises from the climate simulations. In general, Northern and Central regions present larger variability compared to the Southern regions and the Islands. Although at this scale the majority of the results fall within a reasonable range of the central estimate, some values deviate consistently from those of the other ensemble simulations, particularly in the 2050s and 2080s. For example in the 2080s the region Abruzzi shows a range of EAOL between 0.02 and 0.10 percent of GRP, obtained for the climate simulations SMHI-RCA-BCM and CLM-Had-CM3 respectively.

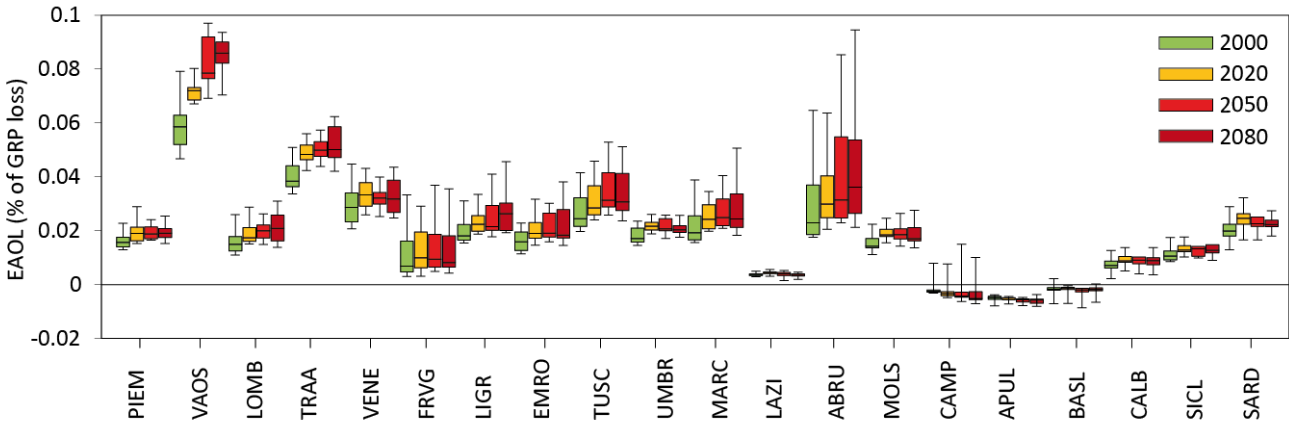

Figure 18: Expected annual output loss (percentage of GRP) by NUTS2 region for the 2000s, 2020s, 2050s, 2080s under climate change. The flood protection standard is assumed constant of 1 per 100 years. Ensemble-based average estimates and five-numbers summaries based on the 12 climate simulation under the A1B emission scenario.

4.3.2. Climate change adaptation

Climate change adaptation benefits (avoided losses) are estimated according to the two risk management scenarios described in Section 4.2.5.2. Here, we refer at adaptation as flood protection only. Benefits are calculated as the difference between the EOAL of the *no adaptation* scenario, i.e. protection levels (in the future) corresponding to the 1 per 100 year current protection standard, and the *adaptation* scenario, i.e. constant 1 per 100 year protection standard over time. The same procedure is applied to Jongman's protection standards.

The ensemble-average EAOLs for Jongman's protections standards, under the A1B-SRES emission scenario, are reported in Table 17. The ensemble-average EAOL without adaptation (*no adaptation* scenario) for Italy as a whole is estimated at 624 million Euro/year by the 2080s. Compared to the *adaptation* scenario, output national losses are more than three times larger. The highest increase deriving from *no adaptation* are reported in the Aosta Valley and Trentino Alto Adige(around 8 times larger than the a*daptation* scenario, i.e. +640 percent of increase). This is probably due to the fact that the two regions of the North are mostly mountainous, they are characterized by large exposure (i.e. constructed area located along the rivers) in narrow and steep valleys, and they hydrology is consistently affected by climate change. For example, without adaptation, the ensemble-based average probability of flooding in the Aosta Valley increases from 1 per 131 years to 1 per 20 years. In Trentino Alto Adige the change is from 1 per 157 years to 1 per 50 years. A consistent difference of output losses due to lack of adaptation is also reported in other regions of the North like Liguria (+452 percent), Veneto (+425 percent) and Lombardy (+316 percent). Because of the size of their regional economies, in Lombardy and Veneto the ensemble-based average EAOL exceed 100 million Euro/year, with 142 an 122 million Euro/year respectively. Without adaptation, Lombardy alone accounts for almost 23 percent of the national EAOL, increasing from around 17 percent in the *adaptation* scenario. Veneto accounts for around 20 percent of the total, almost doubling its share of losses. In the *no adaptation* scenario the Northern regions account for 77 percent of national output losses, while in the *adaptation* scenario the share of the North is around 54 percent. In the rest of Italy, most of the output losses are recorded in Tuscany (around 10-12 percent in both scenarios). In the Center the difference of EAOL between the two scenarios is lower compared to the North, and it has larger variability. For example in Tuscany in the *no adaptation* scenario the EAOL increases by around 2.5 times, while in the Marche the increase is 50 percent. In the South and the two scenarios provide EAOLs of the same order of magnitude, but higher variability (from +50 in Basilicata to – 73 percent in Calabria). It is worth to highlight that a negative difference from the two scenarios represents a decrease of losses or an increase of gains (e.g. Apulia). Therefore in the *no adaptation* scenario the South accounts for only 8 percent of the national EAOL. The largest difference appears in Sicily where climate change effects influence positively the magnitude of output losses, reducing the share of the region from 15 to around 3 percent of the total. It is worth adding that in the *no adaptation* scenario, if the probability of flooding reduces (e.g. in Apulia) the physical protection remains constant but losses (gains) reduce (increase) because of the different probability of the same river discharge.

Table 16: Expected annual output losses per region and Italy as a whole. Ensemble-based average (in million Euro, constant 2004 prices) for the regional flood protection standards based on Jongman et al. 2014. Negative values represent gains if monetary values (e.g. ITF3, ITF4, ITF5) and decreases if percentage values. Note: in this table we refer to adaptation as the maintenance of constant flood protection standards over time.(*) In Campania, the EAOL in the adaptation scenario is negative (i.e. a gain), while the EAOL in the no adaption is positive (a loss).

Group	Code	Name	EAOL 2080 w/ adapt	EAOL 2080 w/o adapt	Change w/o vs w/	w adapt share of IT	w/o adapt share of IT
			mil Euro/y	mil Euro/y	%	%	%
NW	ITC1	Piedmont	14.2	51.9	264.3	7.0	8.3
	ITC2	Aosta Valley	2.1	15.5	640.4	1.0	2.5
	ITC3	Liguria	6.4	35.4	452.4	3.1	5.7
	ITC4	Lombardy	34.1	142.0	316.5	16.7	22.8
NE	ITD1-2	Tren. Alto Adige	8.6	63.1	634.7	4.2	10.1
	ITD3	Veneto	23.2	121.9	425.1	11.4	19.5
	ITD4	Friuli Ven. Giulia	4.4	16.9	285.0	2.1	2.7
	ITD5	Emilia Romagna	16.2	35.6	120.5	7.9	5.7
CTR	ITE1	Tuscany	24.0	65.2	171.5	11.8	10.4
	ITE2	Umbria	2.5	5.8	134.4	1.2	0.9
	ITE3	Marche	8.5	13.0	51.8	4.2	2.1
	ITE4	Lazio	3.7	7.3	98.0	1.8	1.2
S	ITF1	Abruzzi	11.2	16.5	46.7	5.5	2.6
	ITF2	Molise	2.6	2.9	11.5	1.3	0.5
	ITF3	Campania	-0.7	7.0	1086.5*	-0.3	1.1
	ITF4	Apulia	-8.7	-10.5	-21.3	-4.2	-1.7
	ITF5	Basilicata	-0.3	-0.2	49.8	-0.2	0.0
	ITF6	Calabria	5.3	1.4	-73.1	2.6	0.2
ISL	ITG1	Sicily	30.9	20.2	-34.6	15.1	3.2
	ITG2	Sardinia	16.0	13.2	-17.2	7.8	2.1
	IT	ITALY	204.1	624.0	205.7	100.0	100.0

The reduction of output losses per region, i.e. the ensemble-based average benefits, of the risk management strategy *adaptation* is shown in Table 17. In Italy as a whole, *adaptation* provides a benefit of around 420 million/year, reducing output losses in the 2080s by 63 percent compared to the *no adaptation* scenario. The benefits are not homogeneously distributed. Largest benefits are expected in the North, with Lombardy reducing its output losses by 108 million Euro/year (-76 percent from the *no adaptation* scenario). As already highlighted the benefits of adaptation are not evident in Southern regions, because of the modification (positive) of flood probability due to climate change. The *adaptation* scenario reduces completely the output losses of Campania, but leaves a consistent residual loss in other regions, particularly (according to the size of EAOL): Lombardy, Tuscany, Veneto, Emilia Romagna, Piedmont and Abruzzi.

Table 17: Benefits from adaptation. Ensemble-based average (in million Euro, constant 2004 prices) for the regional flood protection standards based on Jongman et al. 2014. Not applicable (n.a.) refers to regions where flood risk (in terms of GRP loss) decreases with climate change. Note: in this table we refer to adaptation as the maintenance of constant flood protection standards over time.

Group	NUTS code	Name	Benefits from adapt	Reduction of losses
			mil Euro/year	%
NW	ITC1	Piedmont	37.6	72.6
	ITC2	Aosta Valley	13.4	86.5
	ITC3	Liguria	29.0	81.9
	ITC4	Lombardy	107.9	76.0
NE	ITD1-2	Tren. Alto Adige	54.5	86.4
	ITD3	Veneto	98.7	81.0
	ITD4	Friuli Ven. Giulia	12.5	74.0
	ITD5	Emilia Romagna	19.5	54.7
CENTER	ITE1	Tuscany	41.2	63.2
	ITE2	Umbria	3.3	57.3
	ITE3	Marche	4.4	34.1
	ITE4	Lazio	3.6	49.5
SOUTH	ITF1	Abruzzi	5.2	31.9
	ITF2	Molise	0.3	10.3
	ITF3	Campania	7.7	100.0
	ITF4	Apulia	n.a.	n.a.
	ITF5	Basilicata	0.2	n.a.
	ITF6	Calabria	n.a.	n.a.
ISL	ITG1	Sicily	n.a.	n.a.
	ITG2	Sardinia	n.a.	n.a.
	IT	ITALY	419.9	67.3

4.3.3. Changes in industries' output

The effects of flooding are not homogeneously distributed across the economic sectors. The R-CGE model is able to capture these effects through the change of the production of commodities for each sector and region. For example, the ensemble-based average production losses caused by a flood event with an associated probability of 1 per 100 years in the 2080s (Table 18 in the Appendix), show that the industrial sectors (e.g. processed food, light and heavy manufacturing, utility and construction) are strongly affected in the Aosta Valley, with a change in the output of commodities of around ten percent (higher for utilities and construction, 14 and 34 percent respectively). Excluding construction, the same sectors are strongly affected also in Trentino Alto Adige (from 9 to 13 percent). The industrial sectors (excluding construction) are also affected, to a lesser extent (from -5 to -2 percent), in Veneto, Piedmont, Abruzzo, Molise, Calabria and Sicily. The industrial sectors of Lombardy, Tuscany and Emilia Romagna experience production losses lower than -2 percent. The highest impacts in the construction industry are recorded in the Aosta Valley (already mentioned) Veneto ad Tuscany (-8 percent), Lombardy, Piedmont and Sardinia (-3 to 4 percent). The largest impacts on the cropping sectors are experienced in Abruzzo (around -10 percent), Tuscany (around -5 percent) and Lombardy (-5 percent for crops and -1.5 for other crops). The livestock production is highly affected in Basilicata (-4.5 percent), Lombardy (-3.6 percent), Marche, Calabria, Sicily and Liguria (between 2 and 3 percent).

In order of magnitude the services are affected in: Marche, Liguria and Trentino Alto Adige (-5 percent), Tuscany, Abruzzo and Sardinia (-4 percent), Emilia Romagna (-3 percent) and Piedmont, Lombardy, Veneto, Umbria (-2 percent). The impacts to the transportation sectors are larger in Trentino Alto Adige (-10 and -8 percent in the transport and air transport sectors respectively), Abruzzo and Marche (around -3 percent), Veneto (-3 percent) and Sicily (-4 percent to the transport sector).

In terms of sectorial production, climate change generally impacts more in the North than the South. The results of our model highlight that the highest increase of losses is in Lombardy (all sectors), Friulia Venezia Giulia (mainly industrial sectors), Tuscany (all sectors), Trentino Alto Adige and Aosta Valley (all sectors excluding cropping). The industrial sector also suffers an increase of losses in Abruzzi and Emilia Romagna.

4.4. Discussion of the results

Compared to typical ex-post disaster assessments where output losses are estimated for a single flood event in a given year (Carrera et al 2015), ex-ante risk assessments are better represented by the expected annual output loss (EOAL), which is a potential economic damage per year (Euro/year). Our results show that the aggregated ensemble-based EAOL in the 1980s is 164-193 million Euro/year (undiscounted 2004 prices) depending on the average flood protection standards, calibrated per each region (Jongman et al 2014) or homogenously distributed as 1 per 100 years respectively. In the *adaptation* scenario, EAOLs increase by the 2080s to 204-214 million Euro/year (undiscounted 2004 prices) under the same flood protection standards assumptions. In the *no adaptation* scenario EAOLs in the 2080s raise to 624-684 (undiscounted 2004 prices), showing a consistent increase from the *adaptation* scenario. Losses are not distributed homogeneously across the country. Some regions, typically the largest economies of the North (i.e. Lombardy and Veneto), have larger losses compared to the regions in the South. Under climate change and *no adaptation*, the distribution of losses in terms of percentage of GRP change is strongly affected by the topographical and climatic characteristics of each region. Indeed, Valle d'Aosta and Trentino Alto Adige experience GRP's losses larger than 0.2 percent/year, while Puglia and Basilicata small gains (0.018 and 0.002 percent respectively). The benefits (avoided losses) from adaption follow the same distribution. In absolute terms (Euro/year) they are higher in the largest economies of the North, in relative terms (GRP change percentage/year) they are larger in the small mountainous regions of the Alps (i.e. Valle d'Aosta and Trentino Alto Adige). It is worth noting that under the *adaptation* scenario, Abruzzi, Molise, Sardinia and Sicily experience a relatively large percentage of GRP reduction (around 0.05 percent/year), the last two having also a significant EAOLs (in the same order of magnitude of the largest economies in the North).

The R-CGE model is able to unravel the impacts into differentiated effects in regional economies. Thus losses in the regions of the North and the Centre are partially compensated by (small) economic gains in some regions of the South. This occurs because of the interconnectivity of the economic system, the mobility of productivity factors and substitution of goods. Instead, the propagation of impacts beyond national border is negligible and the EU and global GDP is in practice unaffected.

The validation of our results is unfeasible, because of the impossibility to work with non-disaster counterfactuals. However, the National Research Council's AVI (Damaged Urban Areas) archive provides a dataset which can be used for comparison purposes. The AVI archive provides information about flood and landslide risk in Italy. The database covers systematically the period 1900-2002, with sporadic data from the 1500. The dataset provides information about the number of events, their location and the damage to the population in terms of number of fatalities (Guzzetti and Tonelli 2004). The dataset accounts for 10,159 hydrological-related fatalities, and 4,566 events. Applying a very basic economic coefficient (GDP2000/capita) to each region, we observe that the regions of the North underwent 76 percent of the losses. Veneto alone account for 27 percent of the losses, Piedmont 19 percent, Lombardy and Trentino Alto Adige 9 percent. Campania accounts for a very high fatality rate, which multiplied by the GDP/capita coefficient constitutes 10 percent of the total impacts. Although we acknowledge the fact that this is a very rough estimation, it still provides an indication of the distribution of potential impacts, in the absence of more detailed data on economic losses. The observed distribution of losses, partially confirms the results of our model, which simulates larger losses in the regions of the North. The relative high percentage of losses recorded in Campania is mainly due landslide risk, which is extremely high in this region. For example we recall the landslide of Sarno in 1988, which killed 110 persons, and the hydrogeological disaster occurred in 1954 in the Province of Salerno (Vietri sul Mare), which caused 318 fatalities. In both events fatalities were mainly due to landslides and wet mass movements (Esposito et al 2004).

The exposure-hazard input data of this work are based on Feyen et al. (2012) and Rojas et al. (2013). The former estimated the current expected annual loss (EOL) (i.e. asset loss) in Italy as 800 million Euro/year (2006 prices), increasing by the end of century to 2,400-2,900 million Euro/year (undiscounted 2006 prices). As expected, the potential output losses estimated in this study are lower than the potential asset losses estimated in Feyen et al (2012). This implies that, up to a certain degree, the economic system is capable to buffer the shock of a disaster (e.g. a flood event), i.e. the loss of capital, land and labour. Hallegatte (2008) estimated that for a given flood event (in this case

Katrina), output losses attain an amount equal to asset losses when asset losses exceed 200 billion US dollars (Hallegatte 2008). Obviously, this is not the case of our analysis. However, if we assume a natural topography without protection against flooding (i.e. dykes and levees), a flood event across Northern Italy with a probability of 1 per 250 years may lead to an aggregated output loss of almost 15.7 billion Euro in the 2000s and 16.8 billion Euro (undiscounted 2004 prices) in the 2080s in the affected regions, considering adaptation. Lombardy would have the highest loss (5.4 billion Euro), followed by Veneto (3.8 billion Euro), Emilia Romagna (2.5 billion Euro) and Piedmont (2 billion Euro). The aggregated asset loss obtained with the same event and no protection standards, may lead in the 2000s to an expected loss of 44.6 billion Euro (undiscounted 2006 prices) (obtained from the Feyen et al (2012) dataset). In this case asset losses are three times larger than output losses.

4.5. Conclusion and policy implications

In this paper we apply the physical drivers of risk (exposure and hazard) developed by Feyen et al (2012) and Rojas et al (2013) to a regionally calibrated global CGE model (R-CGE) to estimate the regional EAOL per region and Italy as a whole. We calculate current and future EAOLs for the period 1961-2011 according to the 12 climate experiments developed by the ENSEMBLES EU Project (Van der Linden and Mitchell 2009). We estimate future impacts under the SRES A1B emission scenario but we do not take into consideration socio-economic changes. We assess short-term effects (1 year) on a static economy (2004). Because of the time frame of our analysis, the economic benefits of reconstruction are not considered.

We simulate two risk management scenarios. In the *adaptation* scenario we find that in Italy the current ensemble-based aggregated EAOL is 164 million Euro/year, increasing by the end of the century to 204 million Euro/year (constant 2004 prices). That is, if flood protection standards are constantly upgraded to the current levels, climate change will cause a 25 percent increase of the EAOL. In the *no adaptation* scenario, EAOLs are projected to increase up to 624 million Euro/year. That is, if protection standards are not upgraded, economic losses will increase fourfold by the end of the century.

Clearly, in such of an heterogeneous territory like Italy, the damage is not homogeneously distributed. Some regions are more affected than others. The R-CGE is able to disentangle, through substitution and mobility, the differential economic feedbacks of each region in the broad national economic context. For example, some regions (e.g. Puglia) experience positive effects on GRP and production. Because of the interconnectivity of the model, the economic benefits are achieved to the detriment of other regions with higher sensitivity to flood risk. Considering the *adaptation* scenario regions such as Lombardy, Veneto, Tuscany, but also Sicily, in the South, hold the majority of losses.

On the other hand in the *no adaptation* scenario the largest part of losses are shared amongst (in order of magnitude): Lombardy, Veneto, Trentino Alto Adige, Tuscany and Piedmont. Counterintuitively *adaptation* produces negative effects in the South (excluding Abruzzi and Molise). This effect is due to the reduction of impacts in the largest economies of the North, provided by the upgrading of flood protection standards. As a consequence, Southern regions might increase (decrease) their losses (gains). Therefore, in an interconnected national economy and under the assumptions considered in this study, the upgrading of flood protection standards does not provide benefit to the regional economies of the South. However it is important to highlight that this study consider only tangible economic impacts of flood risk (excluding landslides and wet mass movements) disregarding social effects (e.g. loss of life, displacement) and intangible impacts.

Overall, the aggregated benefits of adaptation are substantial. Adaptation could reduce the aggregated EAOL by almost 70 percent. Northern regions might experience the largest benefits (up to 86 percent reduction of EAOLs in the Aosta Valley and Trentino Alto Adige), while the regions of Centre at a lower rate. However adaptation comes at a cost and might face several constrains, particularly against upgrading flood protection standards. Indeed, in the Italian socio-environmental context, the modification of river embankments is not a feasible policy option, nor a convenient one. Recent European initiatives against flood risk, including the EU Flood Directive (2007/60/EC) and the Climate Change Adaptation Strategy (EC 2013), have already called for a change of paradigm in relation to flood risk. These initiatives suggest the replacement of standard flood protection measures (e.g. the construction of river embankments) with more efficient flood risk mitigation strategies, such as flood retention. In Italy this is further reinforced by the National Climate Change Adaptation Strategy and by the water management strategies implemented by River Basin Authorities (e.g. the AdBPo, Water Balance Plan). In this terms, the reinforcement of flood retention capacities by means of retention basins or polders (i.e. the lateral diversion of the water) is seen as one of the most efficient solution to control a flood wave (Munich Re 2014). With the support of reliable and accurate forecasting, retention areas can absorb the volume of water required to cap flood peaks. Moreover the retention areas intended for large events can be used for agricultural purposes and, if appropriate compensation is paid, all parties involved can benefit. Therefore a cost recovery approach for flood protection services (as foreseen in the EU Water Framework Directive (ref)) might be useful to enhance the development of water retention areas and, at the same time, provide financial support for the implementation of disaster risk reduction strategies. However, risk mitigation policies shall not forget about existing hard infrastructures. In particular, if controlled flood measures are implemented, it is essential to maintain and reinforce current embankments to avoid their collapse during controlled overtopping. The outcomes of this work provide evidence about the need of risk mitigation policies, those specific development surely require further investigations.

Concluding, in this paper we argue that: a) output losses might be a consistent component of flood risk; b) because of this, the assessment of potential output losses shall not be further neglected in flood risk assessments and flood losses database, which normally focus on the assessment of asset losses only; c) the aggregated current expected annual output loss in Italy is around 160 million Euro/year rising fourfold without adaptation by the end of the century; d) upgrading flood protection standards could reduce 70 percent of the aggregated expected annual output loss; e) the benefits of adaptation to flood risk are heterogeneous across the country, with the Northern regions benefiting more than the regions of the Center and particularly the South; e) the upgrade of flood protective standards reduce the EAOL consistently. Risk mitigation policies aiming at flood protection shall be pursued enhancing flood retention capacities, through polders, controlled flooding areas and retention basins. River embankments shall be properly maintained and reinforced to avoid failure from controlled overtopping.

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4.6. Appendix

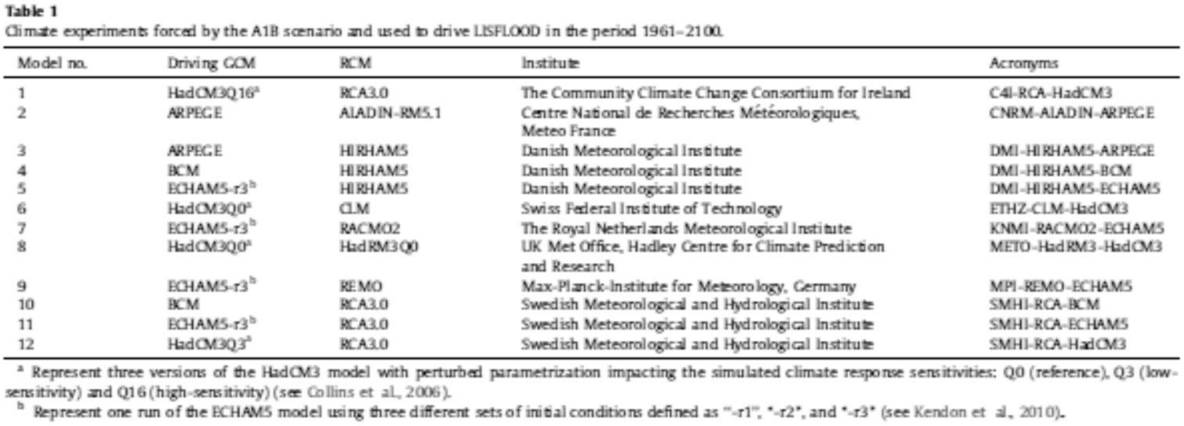

Table 1

Climate experiments forced by the A1B scenario and used to drive LISFLOOD in the period 1961–2100.

Model no.	Driving GCM	RCM	Institute	Acronyms
1	HadCM3Q16^{a}	RCA3.0	The Community Climate Change Consortium for Ireland	C4I-RCA-HadCM3
2	ARPEGE	ALADIN-RM5.1	Centre National de Recherches Météorologiques, Meteo France	CNRM-ALADIN-ARPEGE
3	ARPEGE	HIRHAM5	Danish Meteorological Institute	DMI-HIRHAM5-ARPEGE
4	BCM	HIRHAM5	Danish Meteorological Institute	DMI-HIRHAM5-BCM
5	ECHAM5-r3^{b}	HIRHAM5	Danish Meteorological Institute	DMI-HIRHAM5-ECHAM5
6	HadCM3Q0^{a}	CLM	Swiss Federal Institute of Technology	ETHZ-CLM-HadCM3
7	ECHAM5-r3^{b}	RACMO2	The Royal Netherlands Meteorological Institute	KNMI-RACMO2-ECHAM5
8	HadCM3Q0^{a}	HadRM3Q0	UK Met Office, Hadley Centre for Climate Prediction and Research	METO-HadRM3-HadCM3
9	ECHAM5-r3^{b}	REMO	Max-Planck-Institute for Meteorology, Germany	MPI-REMO-ECHAM5
10	BCM	RCA3.0	Swedish Meteorological and Hydrological Institute	SMHI-RCA-BCM
11	ECHAM5-r3^{b}	RCA3.0	Swedish Meteorological and Hydrological Institute	SMHI-RCA-ECHAM5
12	HadCM3Q3^{a}	RCA3.0	Swedish Meteorological and Hydrological Institute	SMHI-RCA-HadCM3

[a] Represent three versions of the HadCM3 model with perturbed parametrization impacting the simulated climate response sensitivities: Q0 (reference), Q3 (low-sensitivity) and Q16 (high-sensitivity) (see Collins et al., 2006).

[b] Represent one run of the ECHAM5 model using three different sets of initial conditions defined as "-r1", "-r2", and "-r3" (see Kendon et al., 2010).

Figure 19: ENSEMBLE EU Project – 12 climate experiments

Table 18: ensemble-based average industry output (percentage change from baseline) of commodity i in region r, for a flood event with an associated probability of 1 per 100 years, in the 2080s. Positive values higher than 2 percent are highlighted in green, between -2 and -5 percent in yellow, less than -5 percent in red.

Code	Region	Crops	OtherCrops	Livestock	Forestry	Fishing	Minerals	ProcFood	LightManif	HeavyManif	Utilities	Construction	Services	Transport	AirTrans	CGDS
ITC1	Piedmont	0.4	0.5	-1.0	-0.1	-3.0	-4.9	-1.6	-2.0	-1.8	-2.5	-4.1	-1.6	-2.3	-1.8	-2.5
ITC2	Aosta Valley	9.2	0.1	-0.5	0.9	-1.6	-0.7	-10.1	-12.2	-10.6	-14.2	-33.6	-0.9	-0.6	-8.0	-21.9
ITC3	Liguria	1.2	-0.8	-2.0	0.1	-0.2	1.3	0.0	1.7	1.1	0.0	5.7	-5.1	0.4	0.7	-2.7
ITC4	Lombardy	-4.8	-1.5	-3.6	-1.3	-2.0	-0.6	-1.7	-1.1	-1.3	-1.7	-3.9	-2.2	-2.2	-1.5	-2.4
ITD1-2	Tren. Alto Adige	0.7	-6.2	0.3	2.3	-1.7	-0.6	-9.3	-12.0	-11.2	-12.9	6.0	-4.9	-10.1	-8.3	-4.0
ITD3	Veneto	-0.5	-0.1	-0.7	-0.7	-0.4	-3.5	-2.7	-4.1	-3.9	-4.6	-8.1	-2.1	-2.8	-2.0	-3.7
ITD4	Friuli Ven. Giulia	0.3	-1.4	-1.2	0.0	-1.1	-0.8	-1.4	-1.3	-1.2	-1.1	2.2	-1.5	-0.8	-2.5	-1.4
ITD5	Emilia Romagna	-1.7	0.6	-1.1	-0.2	-0.9	-1.8	-1.8	-1.7	-1.7	-2.0	-1.0	-2.7	-2.1	-1.7	-1.7
ITE1	Tuscany	-4.3	-5.0	-1.8	0.6	-1.0	-6.2	-1.7	0.1	-1.2	-1.6	-8.2	-4.2	-1.7	-1.4	-4.0
ITE2	Umbria	-1.3	0.9	-0.9	1.3	-1.0	-5.8	-2.7	-2.9	-2.6	-3.4	-0.1	-2.1	-2.8	-1.6	-1.4
ITE3	Marche	-1.9	0.7	-2.8	0.7	-0.4	-1.8	-1.5	0.6	-0.7	1.1	2.1	-5.3	-3.8	-2.3	-3.0
ITE4	Lazio	0.3	0.5	-1.2	0.4	-0.7	-0.2	-0.4	0.3	0.3	0.0	1.2	-0.6	-0.5	0.1	-0.9
ITF1	Abruzzi	-11.6	-9.2	0.8	0.9	-0.2	-0.8	-3.5	-4.3	-3.3	-4.2	-1.1	-4.5	-3.3	-2.6	-3.2
ITF2	Molise	0.7	0.3	1.7	0.9	-0.1	-0.6	-4.6	-4.9	-4.1	-3.2	1.5	-1.4	-0.8	-0.8	-1.4
ITF3	Campania	0.0	-0.1	-1.5	-1.0	-0.4	0.0	-0.6	-0.5	-0.4	0.5	0.0	0.3	-0.3	-2.1	-0.6
ITF4	Apulia	-0.8	0.1	-0.8	-0.8	-0.2	0.3	0.2	0.8	0.7	0.6	2.5	0.2	-0.2	-0.4	-0.1
ITF5	Basilicata	-0.6	0.4	-4.5	-0.3	-1.6	0.1	0.6	1.0	0.5	0.2	-0.7	0.1	0.2	-0.5	-0.4
ITF6	Calabria	-1.9	0.4	-2.5	0.0	-0.4	0.0	-2.4	-2.2	-2.5	-1.9	0.6	-0.7	-2.0	-0.9	-0.9
ITG1	Sicily	-2.1	-0.8	-2.1	-0.8	-0.5	-0.7	-2.9	-3.6	-2.5	-2.7	0.4	-0.9	-4.1	-0.7	-1.1
ITG2	Sardinia	0.7	1.0	0.0	0.6	-0.7	1.2	-0.1	-0.5	0.6	-0.1	-2.7	-3.6	-0.5	-1.1	-3.7

Table 19: ensemble-based average industry output of commodity i in region r, for a flood event with an associated probability of 1 per 100 years: percentage change of industry output reduction in the 2080s from the 1980s. Negative values (reduction of losses) lower than -20 percent are highlighted in green, between 20 and 50 percent in yellow (moderate increase of losses), more than 50 percent (significant increase of losses) in red.

Code	Region	Crops	OtherCrops	Livestock	Forestry	Fishing	Minerals	ProcFood	LightManif	HeavyManif	Utilities	Construction	Services	Transport	AirTrans	CGDS
ITC1	Piedmont	-31	-21	17	33	15	5	5	0	1	3	-2	7	10	15	6
ITC2	Aosta Valley	-30	-163	21	-31	15	26	22	24	24	24	29	-3	15	106	27
ITC3	Liguria	7	104	18	-43	12	-21	33	-14	-14	35	-18	16	-32	-25	17
ITC4	Lombardy	24	121	17	10	18	24	22	29	26	26	33	22	23	18	25
ITD1-2	Tren. Alto Adige	-19	14	1	-20	18	35	15	15	15	14	-19	18	13	23	18
ITD3	Veneto	-6	-36	22	12	16	12	10	7	10	11	21	15	19	15	17
ITD4	Friuli Ven. Giulia	-17	11	30	-149	43	2757	111	710	408	329	-16	31	65	21	50
ITD5	Emilia Romagna	9	-38	17	-5	19	7	30	35	31	31	-1	19	22	19	22
ITE1	Tuscany	20	21	22	-11	29	10	26	84	44	32	13	14	22	14	16
ITE2	Umbria	-8	-26	17	-2	14	-2	2	-4	-3	-1	-54	3	10	5	3
ITE3	Marche	16	-10	23	-33	67	18	37	35	74	19	-16	16	39	24	21
ITE4	Lazio	-69	-52	24	-14	12	-28	-17	-1487	-235	-129	-27	-24	-13	-105	-11
ITF1	Abruzzo	17	54	-145	-69	-3	-13	46	57	55	57	45	30	44	31	36
ITF2	Molise	-18	-132	-2	-9	32	-3	3	0	2	3	-9	5	8	18	6
ITF3	Campania	-95	-70	15	21	14	-121	-21	-36	-41	-185	-94	-14	-26	0	-14
ITF4	Apulia	-10	-659	11	6	1	-58	-83	-25	-30	-15	-17	15	28	10	66
ITF5	Basilicata	8	-42	-30	7	14	-13	-108	-60	-103	-339	-24	31	-11	2	-11
ITF6	Calabria	-2	-59	7	-343	11	-205	-1	-4	-3	-4	-22	14	5	4	9
ITG1	Sicily	-3	-8	6	4	3	-10	7	5	7	6	-36	3	1	-2	5
ITG2	Sardinia	-25	-16	4	-2	2	-5	-69	-39	-47	-53	-6	-4	-3	-1	-2

Table 20: estimation of losses distribution in Italy according to the AVI archive.

Code	**Name**	**Flood and landslides**		**Flood***	**GDP/capita**	**Losses**
		Events	**Fatalities**	**Fatalities**	**coeff**	**%**
ITC1	Piedmont	645	1,714	785	1.2	18.4
ITC2	Aosta Valley	82	265	121	1.3	3.3
ITC3	Liguria	168	214	98	1.0	2.1
ITC4	Lombardy	442	877	402	1.4	11.1
ITD1-2	Tren. Alto Adige	190	711	326	1.3	8.7
ITD3	Veneto	336	2,361	1,081	1.2	26.9
ITD4	Friuli Ven. Giulia	146	360	165	1.1	3.8
ITD5	Emilia Romagna	168	188	86	1.3	2.3
ITE1	Tuscany	241	184	84	1.1	1.9
ITE2	Umbria	86	49	22	1.0	0.5
ITE3	Marche	94	96	44	1.0	0.9
ITE4	Lazio	236	127	58	1.2	1.4
ITF1	Abruzzi	84	26	12	0.9	0.2

ITF2	Molise	35	9	4	0.8	0.1
ITF3	Campania	612	1,668	764	0.7	10.1
ITF4	Apulia	157	128	59	0.7	0.8
ITF5	Basilicata	122	87	40	0.7	0.6
ITF6	Calabria	218	370	169	0.6	2.2
ITG1	Sicily	243	514	235	0.7	3.2
ITG2	Sardinia	261	211	97	0.8	1.5
IT	ITALY	4,566	10,159	4,652	1.0	100.0

5. Synthesis

5.1. Findings of the thesis

Sound risk assessment is essential for developing effective disaster's risk mitigation policies. This thesis investigates social vulnerability and the economic cost of flood risk, which are indeed two significant components of risk. The thesis provides a comprehensive analysis of risk in the Po river basin, including social vulnerability. Moreover the thesis presents an innovative integrated impact assessment model for ex-ante and ex-post economic analysis of disasters. The model is applied to two case studies. The ex-post analysis re-examine the economic damage of the Po 2000 flood event, including the assessment of wider economic losses. The ex-ante analysis estimates the expected annual output losses under current and future climate Italy, providing insights about the benefits of climate change adaptation.

In details:

- Section 2 focuses on social vulnerability. A modified version of the hazard of place model (Cutter 1996) is applied to the Po river basin. Selected criteria are combined in a Multi Criteria Analysis (MCA) type analysis to assess the social vulnerability to fluvial flooding at municipality scale. The results show that some areas of the basin are more vulnerable than others, particularly the area with higher population densities. Moreover the vulnerability profile shows high levels of vulnerability in the mostly mountainous region of Valle d'Aosta (this regions has also been identified as extremely vulnerable in Section 4). This work shows that the distribution of risk is highly dependent on the distribution of social vulnerabilities, which shall not be neglected in the development of the flood risk mapping required by the Flood Directive (2007/60/EC).
- Section 3 is an ex-post economic assessment of the 2000 Po river flood in Northern Italy. The event caused major economic losses in the area directly affected, but also outside of the flooded area. Several studies reported different figures of economic damage (up to 8.6 billion Euro from EM-DAT). This figures concerns mainly direct tangible damages, omitting partially or totally indirect effects. The impacted areas is one of the most productive of Italy. Therefore indirect economic effects might be significant. Against this background, this work re-examines the single event's losses. Direct (asset losses) and indirect (output losses) impacts are estimated, although the main focus of the paper is on indirect losses. Directt losses are calculated for comparison purposes only. The methodology consists of the integration of a spatially-based impact model with a sub-nationally calibrated global Computable General Equilibrium model (Narayanan and Walmsley 2008; Standardi et al

2014) to assess output losses. The outcomes of the simulation shows that impacts are distributed heterogeneously across the North, the Center and the South of Italy. The model unravels differentiated effects in sub-national economies, positive or negative as they may be depending on the location of the event. The impacts are reported in term of production and GDP change during a one year period after the event (short term impacts). The results show that indirect losses play an important role in the full social cost of floods. In this case indirect losses account for around 20 percent of direct losses.

- Section 4 provides an ex-ante assessment of the output losses (i.e. indirect losses) expected from fluvial flooding in Italy. The analysis considers a time frame from 1961 till 2100, with the period 1961-1990 considered as the control and calibration period. Climate change is considered with 12 climate experiments, under the SRES A1B emission scenario. Impacts are estimated as expected annual output losses (EAOLs) in terms of GDP and production change at the regional (NUTS2) and country level. Some 14 economic sectors are considered. The study consider two risk management scenarios: adaptation and no adaptation. The results show that, without adaption, EAOL will increase fourfold, up to more than 600 million Euro/year. Losses are not distributed homogenously across the county. The model is able to differentiate losses and adaptation benefits across regions. In this study adaptation refers to upgrading flood protection to changing river discharge conditions. Because of the constrains of increasing flood protection standards in Italy (e.g. through the raising dykes), alternative options are suggested such as increasing retention capacity through the construction of flood retention areas and controlled floods .

5.2. Advancing in the field of disaster's economics

Chapter 3 and 4 of this thesis propose a methodology to advance the understanding of disaster's risk economics. Too often, the economic assessment of natural hazards is limited to the damage to assets directly affected by the event. This is true for a list of hazards, including earthquakes, droughts, sea level rise. In the past years a number of scholars have demonstrated that assessing wider economics effects of natural hazards is feasible and provides sound results.

However, very often the aggregation level of economic models is way to course for policy makers, which work at smaller scale. The integration of bottom-up approaches (like GIS-tools) and top-down methods (like macro-economic models) is not an easy task. This thesis describes an innovative methodology to bridge this gap. The downscaling of macro-economic models and the 'spatialization' of the economy exposure and the hazard, allow to estimate indirect effects of disasters. The flexibility of macro-economic models, coupled with high resolution GIS tools, might be very relevant in assessing the effectiveness and performance of policies aiming at increasing socio-economic resilience.

Moreover the inclusion of indirect losses in disaster's accountancy is essential for the construction of improved natural hazard's database. The need for the development and use of improved economic risk assessment methods, which also consider the wider effects of disasters, has been already highlighted in the (EC 2009) and (EEA 2013). Given the new activation mechanism (based on the Regional Gross Product affected) of the EU Solidarity and Structural Funds (De Groeve et al 2013), the inclusion of indirect effects might be very relevant.

However, a consistent gap concerning intangible losses still exist. Quantifying intangible losses is not an easy task, probably more complicated than indirect losses. Putting a price on immaterial goods has been proposed in previous studies, particularly for ecosystem services (Bateman et al 2011). However they may account for a large part of the impacts. Their inclusion in economic modelling remains a daunting challenge which shall be considered in further research.

5.2.1. Limitations of this work

Most of this thesis focus on fluvial flood risk (although Section 2 refers to wider family of hydrological risks). Fluvial flood risk is very relevant to Italy, but landslide and flash floods have equally important impacts on the society. According to the AVI database less than half of the 10,000 fatalities caused by hydrological risk from the 1900 have been caused by fluvial flooding. Italy is a mostly hilly-mountainous country characterized by a largely diffuse urban and economic environment. These characteristics, combined with a fragile geology particularly in the Apennines, make the Italian territory particularly vulnerable to landslides and wet mass movements. Because landslide hazard is not included in the analysis of Chapter 3 and 4, the results might not provide a full account of expected losses and their distribution across Italian regions. For example, the AVI database shows that the region Campania recorded in the past significant impacts from hydrogeological extreme events. In the analysis of Section 4, Campania lays amongst the less risky areas to flood. Because of this, further research on landslide risk could be beneficial for improving the distribution of expected economic losses across the regions of Italy.

It is important to highlight that the assessment of indirect impacts (i.e. output losses) is still an evolving topic. Although indirect impacts were already considered in 1977 Canter's work on Environmental Impact Assessment (Canter 1977) and in Rose (1997), there is not a widely accepted nor used methodology yet. The focus on indirect impacts comes to the cost of considering several assumptions and to be only-partially able to validate the results. Several assumptions have been to obtain the results presented. In order of importance, the mayor assumptions concerns: a) the time duration of the economic assessment. The economy of the model is static and the impacts are evaluated in the short-tem (one year) without recovery and long-term effects; b) the duration of the disruption to economic sectors. The literature does not provide useful information about the typical, neither specific, duration of production losses per sector. In economic modelling this duration is typically assumed based on expert judgment (Okuyama 2007; Kajitani and Tatano 2014; Santos et al 2014). In this thesis I assumed a duration period ranging from few months to one year; c) the calibration of the model parameters, which are not based on econometric studies but optimization methods. Moreover the validation of the results obtained related to indirect impacts is extremely difficult, almost impossible. The lack of counterfactual conditions where flooding effects are disentangled form other economic disturbances, limits the possibility of validating the results. Moreover as already mentioned, there is no dataset which record systematically this type of losses.

The analysis presented in Section 2 also presents few limitations. The type of vulnerability maps developed are difficult to be considered by policy makers. Social vulnerability is rarely (at least in Italy) included in flood risk mapping. Moreover the equally weighed average aggregation of indicators does not consider any interaction between criteria. On one hand it guarantees the objectivity of the aggregation, but on the other hand it misses completely stakeholder preferences, expert elicitation and the consideration of the interactions between indicators. For example, the contemporarily presence of two criteria could have a different effect than the sum of the two (Zabeo et al 2011). Non-additive methods could be beneficial in understanding synergies and redundancies of criteria (Giove et al 2010).

5.3. Opportunities and further research

More often than not scholars tend to generate simply models to reproduce complex socio-economic-ecological systems and draw general conclusion for all cases. The ‘panacea’ issue is particularly evident in environmental economics studies (Meinzen-Dick 2007; Ostrom et al 2007), where general solution are proposed to different cases, in different contexts. This thesis proposes two methodologies for analyzing social vulnerability and economic impacts of flood risk. Both methodologies are case-specific and their results shall be properly interpreted. Therefore the ambition of this study is to be part of a learning process about flood risk, instead of proposing a ‘panacea’. Even though learning per se does not necessarily lead to improved governance (Brock and Carpenter 2007), particularly in a dynamic context such the socio-economic interaction with climate, better understanding of spatial vulnerabilities (both social and economic) of flood risk might be beneficial to shape successful policies.

In Italy social vulnerability is normally not estimated neither considered by policy makers and stakeholders. The risk maps developed as a requirement of the 2007/60/EC still do not account for social vulnerability. The analysis still lay on the damage to the physical capital assessments based on the assets exposed to a certain hazard. Nor vulnerability or resilience are considered as mitigating-exacerbating factors of risk. In addition to this, there is poor understating of the wider economic effects of flood risk. The EC (EC 2009) has recently call for the creation of an informative and standardize database of the economic consequences of flooding (De Groeve et al 2013). The methodology described in this thesis might be beneficial.

There are wide opportunities for further research on the topics presented in this thesis. First, the number of social vulnerability indicators might be enlarged and the equally average weighted aggregation of indicators might be replaced with non-additive methods. This could better represent the interactions between different characteristics of the same population. Second, econometric studies on existing economic dataset could be beneficial for the calibration of the economic model parameters (the CET and the CES functions) and for the validation of the CGE model's results. Third, there is a need for information about the duration of business inoperability in case of flooding. The elaboration of flood-depth damage functions, such as the ones used in asset loss assessments, could be also beneficial for output loss assessments. Fourth, impact economic models do not normally consider vulnerability or resilience factors. In the case of CGE models, resilience is intrinsically considered within the flexibility of the model. However, small consideration is given to social effects, behavioral preference and the dynamics of societies in the aftermath (and before) a disaster. For example, some authors suggested that after a disaster there might be a nonlinear behaviour of the markets, the shift from profit (or income, welfare) maximisation to other goals, the alteration of market systems, etc. (Böhringer and Löschel 2006; Balbi and Giupponi 2010). Therefore the inclusion of vulnerability and resilience indicators into economic impact assessment models could be extremely beneficial, not only to predict potential losses, but also to assess the performance of risk mitigation policies, and monitor their effects on the society.

Improving our understanding of the interactions between resilience and vulnerability, and the economic outcomes of disasters may finally lead to a beneficial integration of climate change adaptation and disaster risk management. Consequently, relevant policies may benefit from improved information.

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