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Economics of flood risk in Italy under current and future climate

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SUMMARY An integrated impact assessment methodology is developed and applied to estimate current and future economic impacts of flood risk in Italy under climate change. The methodology combines a high resolution spatial analysis 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 from 1980 till 2100. Climate change effects are based on 12 climate simulations. Losses are estimated for two disaster risk management scenarios: with and without adaptation to changing river discharge conditions. Our results show that in Italy, because of climate change, current aggregated ensemble-based expected annual output losses increase 25 percent by the end of the century with adaptation, and fourfold without adaptation, exceeding 600 million Euro per year. The paper provides the distribution of adaptation benefits across regions, which cumulative value exceed 23 billion Euro over the long term (2014-2100) and 11 before 2050.

Keywords: flood risk, impact assessment, output losses, computable general equilibrium, climate change

1. INTRODUCTION

Over the last decades, the analysis of many climate and weather events have shown that anthropogenic activities have influenced the global water cycle causing the modification of precipitation patterns (IPCC 2013). 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 2013). Moreover, the IPCC (2014b) reports with high confidence that the increasing global temperature will very likely increase extreme precipitation events, which will occur in Europe more frequently and with stronger intensity by the end of this century. Growing economies and capital density, increasing demography and inappropriate land use will further expose societies to increasing flood hazards and consequent losses (Pottier et al. 2005; WMO 2008; Maaskant et al. 2009; Wheater and Evans 2009; Bouwer et al. 2010; De Moel and Aerts 2011; Te Linde et al. 2011; IPCC 2012; Hallegatte et al. 2013; Hallegatte 2014a; Jongman et al. 2014b). Some studies already provided quantitative projection of future potential losses of fluvial flooding in Europe (Feyen et al. 2012; Rojas et al. 2013). In general, flood risk assessments focus on the damage to the physical assets (Thieken et al. 2008; Kreibich et al. 2010; Feyen et al. 2012; Rojas et al. 2013; Balica et al. 2013; Aerts et al. 2013; De Moel et al. 2014; Saint-Geours et al. 2014), to the detriment of the analysis of productivity and output changes.

Although over the past years an increasing number of scholars have highlighted the relevance of 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), output losses are generally omitted in losses accounting and disaster risk management (DRM) practices. The literature on output losses provides several methodologies and applications: 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; Koks et al. 2014; 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; Rose and Wei 2013; Rose and Krausmann 2013; Carrera et al. 2015).

Within this context, our paper proposes the integration of a spatially based model of the physical drivers of flood risk (hazard and exposure), with a Regionally-calibrated Computable General Equilibrium (R-CGE) model of Italy, to estimate expected annual output losses (EAOL) in terms of Gross Regional Product (GRP) change per region (at NUTS2 level) and Italy as whole over the period 1980-2100. In order to estimate climate change effects only, our model assumes a static economy and land use over time, which is shocked against a loss of productivity of the primary factors of production. Climate change effects are estimated under two DRM scenarios: with and without adaptation to changing river discharge conditions. We use expected avoided losses as a proxy of the potential benefits of DRM, providing regionally-distributed quantitative evidence of adaptation at regional and national scale.

The remainder of this paper proceeds as follows. In Section 2 we describe the conceptual framework and methodology. In Section 3 and 4 we present and discuss the results. Section 5 concludes the paper providing a critical review of the outcomes, in the broader context of flood risk assessment and DRM.

2. METHODOLOGY

2.1 TERMINOLOGY

The terminology used in this paper distinguish losses in two categories: asset losses and output losses (Rose 2004; Hallegatte 2014b). We focus our analysis on output losses and we use a classic economic indicator, GRP to capture this category of losses. We acknowledge the fact that GRP have similar limitations in measuring output losses, as Gross Domestic Product (GDP). In general this indicator 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 (Hallegatte 2014b). But, on the contrary of GDP which does not represent inequalities and heterogeneity within a country, GRP is more suited to the specific spatial scale of analysis of fluvial flooding (Jonkhoff 2009; Pfurtscheller 2014).

2.2 T GENERAL FRAMEWORK

Our model is conceptually described in Figure 1. From left to right we proceed as follows: (1) hazard: flood extension maps per 5 time steps and 8 return periods are obtained from 12 climate simulations and the LISFLOOD hydrological model; (2) exposure: we match Corine Land Cover (CLC) 2000 classes with 14 economic sectors to obtain a spatially-distributed economy; (3) impact: we overlay hazard and exposure to estimate the area affected per sector, which we translate into a reduction in the capacity of producing goods and services (i.e. the productivity of the primary factors of production: land, capital and labour) per sector per region; (4) output loss: we shock the economic model (R-CGE) with the impact on productivity. We obtain an expected loss (or gain) of GRP per return period and time step; (5) EAOL: from the expected losses we estimate the probability loss curves per region. We set regional flood protection standards (FPS) and we calculate EAOL per region and time step up to 2100.

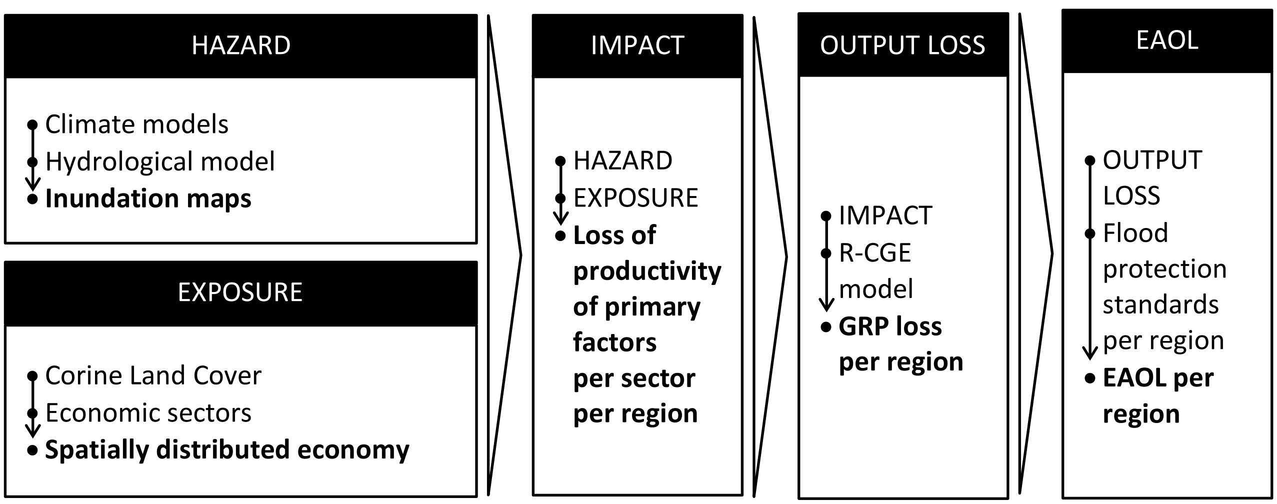

Figure 1: conceptual map of the model.

2.3 HAZARD AND EXPOSURE

Flood input data for this work are provided by the Joint Research Center (JRC) within the EU Project ENHANCE. With similar purposes Rojas et al. (2013) used the dataset to estimate future asset losses in Europe. 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 Feyen et al. (2012), Rojas et al. (2013). In particular, for the climate simulations to Van der Linden and Mitchell (2009), for the hydrological simulation with the LISFLOOD model to Van Der Knijff et al. (2010). Our work considers the outputs of LISFLOOD against 5 time steps (1980, 2000, 2020, 2050, 2080) of 30 years duration up to 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. The hazard component of the model is derived from the extension of the flooded area obtained from the river discharges characterized by a specific probability, which is defined by the return period.

The territory of our analysis is spatially represented, in terms of land use, by Corine Land Cover (CLC) 2000 (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 2 in the Appendix).The matching of land cover classes and economic activities is performed through a qualitative analysis of CLC2000 classes description (EEA 2002) and the economic sectors provided by GTAP (Narayanan and Walmsley 2008). 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 and the services sectors is 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 and one sector to be associated with more than one land use class. Table 3 in the Appendix offers more details on the matching. In synthesis, this approach provide us with a sort of spatially-distributed economy, where economic activities are distributed across the Italian territory based on land cover.

2.4 OUTPUT LOSSES

The impact calculated for each climate simulation is used to shock the R-CGE model. The R-CGE model provides expected output loss (or gain) per region, flood return period and time period, in terms of percentage of GRP change.

For a detailed description of the R-CGE characteristics and functioning mechanisms, we refer the reader to the specific section in the Appendix and to Standardi et al. (2014) and Carrera et al. (2015). For this assessment the model relies on the following assumptions: (a) the shock, represented by the flood event associated with a specific probability, is enforced to the one year point of the disaster occurrence and does not influence precedent or subsequent years. The shock reduces the productivity of the primary factors of production (land, capital and labour) in the affected area; (b) output losses are generated by the disruption of the capacity to produce, which is a consequence of the loss of assets and labour; (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. The time scale of our analysis is one year and the model is static. Each single shock to the economic system translates into a yearly loss of output; g) we consider climate change effects only, disregarding of socio-economic changes (e.g. GDP change over time and land use), which are not accounted for.

2.5 LOSS PROBABILITY CURVES: 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:

$P(E_i \text{ happening}) = p_i$

$P(E_i \text{ not happening}) = (1-p_i)$

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

If the flood does not occur the loss is zero. If the flood occurs the expected loss E(L) for a given year is (Equation 3):

$$(3) \qquad E_i(L) = p_i L_i$$

where L is the associated loss.

For a set of events each with a probability p_i and an associated loss L_i, the EAOL is calculated as the integral of the damage curve truncated at the specific flood protection standard (FPS), which is defined as the minimum statistical probability discharge that leads to flooding. We calculate the integral with the trapezoidal rule (Equation 4):

$$(4) \qquad EAOL = \frac{1}{2}\sum_{i=FPS}^{10,000}\left(\frac{1}{x_i} - \frac{1}{x_{i+1}}\right)\left(E(L)_{i+1} + E(L)_i\right)$$

Where i is the time between two events with expected loss E(L), and FPS is the flood protection standard. The EAOL is calculated up to an event with a return period of 1 per 10,000 years, interpolated over the known return periods.

2.5.1 FLOOD PROTECTION STANDARDS

FPS are based on the dataset developed by Jongman et al (2014), to which we refer for further information. In order to be consistent with the scale of analysis of the R-CGE model, we calculate the average standard protection level per region (Table 4 in the Appendix). In general, flood protection standards 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 typical orography of the territory, and the class of rivers of the Apennines in the Center and the South, which, omitting exceptions like Arno, Tevere, Volturno and few others, have stream-type regimes, which may induce the setting of lower protection standards.

EAOLs are calculated setting to zero all expected losses below the specific regional FPS.

2.5.2 RISK MANAGEMENT SCENARIOS: CLIMATE CHANGE ADAPTATION

In this work we investigated the outcomes of two DRM scenarios named *with adaptation (WA)* and *without adaption (WOA)* to changing river discharge conditions. In the first we assume FPS 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. *WOA*, FPS's 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 the region is protected against. For example we can obtain 85 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 the probability of having the same flood river discharge decreases, because of the modification of precipitation patterns. As a consequence, current FPS increase in the future (in terms of return period). In this case, the EAOL is estimated with the new FPS. That is, protection standards are never physically downgraded but the probability of flooding decreases due to climate change.

The difference between the two DRM scenarios are the avoid losses of adaptation, which we use a proxy of adaptation benefits. It is important to highlight that in this work, we refer to adaptation as upgrading flood protection standards to changing conditions of river discharge, disregarding on how this objective is achieved[1].

3. RESULTS

3.1 DISTRIBUTION OF EAOL: WA SCENARIO

In Italy as a whole EAOL are projected to increase from 164 million Euro in the 2000s to 204 million Euro (constant 2004 prices) in the 2080s. The distribution of losses in uneven across the country. The North bears 50 percent of total losses, the Center 19 percent, the South 4 percent and the Islands 27 percent.

Because of low FPS (1 per 27 years) in 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). Instead, 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 redistribution of losses towards the end of the century to the detriment of Northern regions. In the 2080s Lombardy is projected to be have the highest EAOL (34 million Euro, 17 percent of national losses, 44 percent increase by the 2080s, while

[1] It is very unlikely that adaptation to changing river discharge conditions in Italy will be pursued through the upgrading of river embankments or elevation of dykes. Other interventions focusing on flow peaks reduction, such as retention basins, soil management, re-naturalization of rivers and streams are more likely to be implemented (www.enhanceproject.eu).

Sicily is projected to increase with a slower pace (7 percent). Figure 4 in the Appendix shows the ensemble-based EAOL estimates at regional level over time.

In order to highlight the relative effect of flood risk to regional economies, Figure 2 shows the ensemble-based average estimates of output losses (in percentage of GRP) per region and the variability given by the 12 climate simulations. All regions suffer EAOL lower than 0.1% GRP. In relative terms the Aosta Valley is the one experiencing the highest EOAL. 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. It worth to highlight that Campania, Calabria and particularly Apulia report a net benefit, although the percentage of expected annual output gain is almost insignificant compared to the losses reported by the other regions.

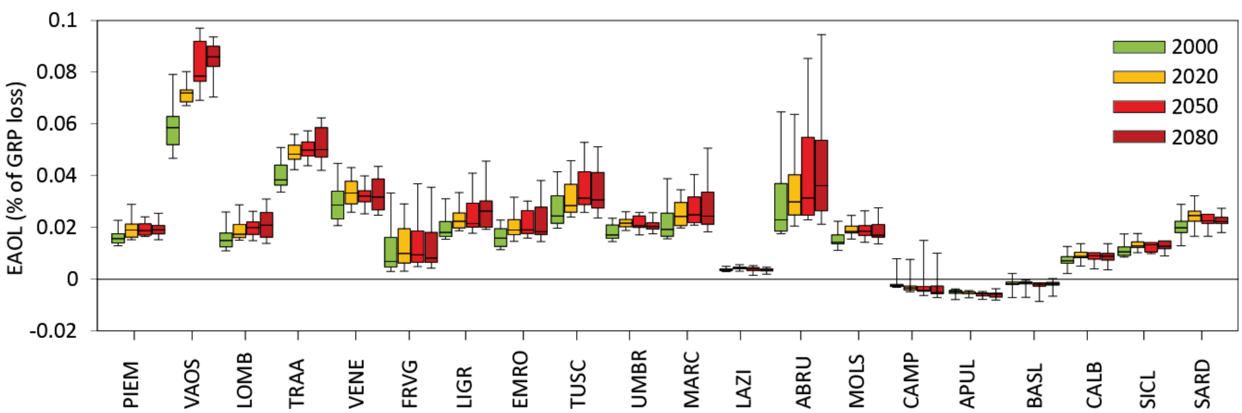

Figure 2: EAOL (in percentage of GRP) by NUTS2 region for the 2000s, 2020s, 2050s, 2080s under climate change. The flood protection standard is assumed constant of 1 per 100 years. Ensemble-based average estimates and five-numbers summaries based on the 12 climate simulation under the A1B emission scenario.

3.2 DISTRIBUTION OF EAOL: WOA SCENARIO

The ensemble-average EAOL in the period 2080s per region, without adaptation to climate change are reported in Table 5 in the Appendix. Under this scenario the ensemble-average aggregated EAOL will reach by the end of the century 624 million Euro/year, which is more than three times larger than the *WA* scenario. The regions Aosta Valley and Trentino Alto Adige report the highest 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 their 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. Because of the size of their regional economies, in Lombardy and Veneto the ensemble-based average EAOL exceed 100 million Euro/year, with 142 and 122 million Euro/year respectively. It is worth adding that in the *WOA* 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.

3.3 ADAPTATION BENEFITS IN THE 2080S

The reduction of output losses per region, i.e. the ensemble-based average benefits of adaptation is shown in Table 1. The aggregated benefits in the 2080s are around 420 million/year, reducing output losses in the 2080s by 63 percent compared to the *WOA* 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 *WOA* scenario). As already highlighted the benefits of adaptation are not as much as evident in Southern regions, because of the modification (decreasing) of flood probability due to climate change. The *WA* 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.

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

Table 1: Ensemble-based average benefits from adaptation (in million Euro, constant 2004 prices). Not applicable (n.a.) refers to regions where flood risk (in terms of GRP loss) decreases with climate change.

3.3.1 MEDIUM AND LONG TERM ADAPTATION BENEFITS

Figure 3 shows the ensemble-based average EAOL at regional level for the five time periods under the two DRM scenarios. Some regions experience a larger divergence of EAOL between the two scenarios, with Northern regions being more affected by the lack of adaptation

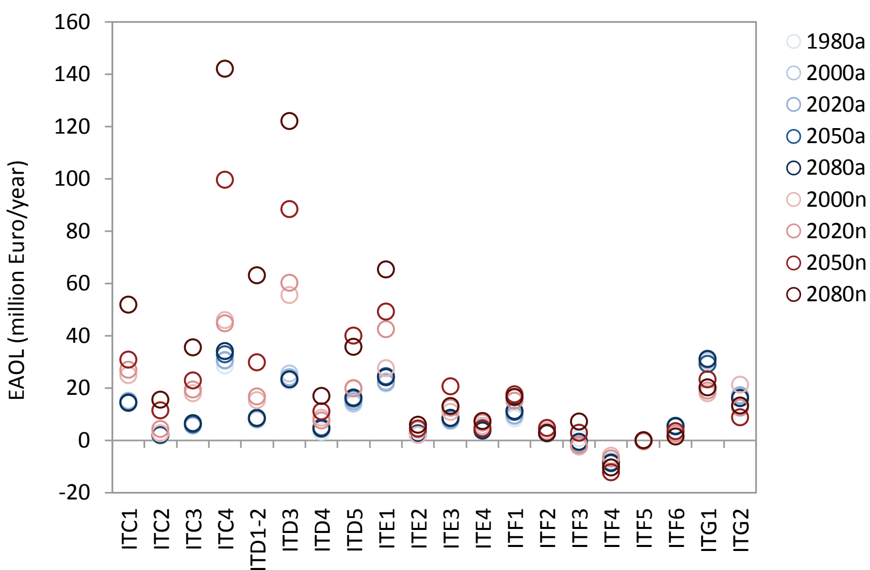

Figure 3: Ensemble-based average EAOL (in million Euro per Year) by region for the 1980s, 2000s, 2020s, 2050s, 2080s periods under climate change and heterogeneous FPS. Blue circles represent the WA scenario (a), while red the WOA (n).

Figure 4 shows the total cumulative aggregated losses over the entire period of analysis (1980-2100). It is worth to highlight that under adaptation the curve is linear, while under the no adaptation the curve increases exponentially with time due to climate change effects and downgraded protection standards. We estimate that over the long-term (2014-2100) the cumulative losses are 40,500 million Euro (undiscounted, 2006 value) or 654 million Euro per year. Over the medium-term (2014-2050) cumulative losses are expected as around 21,800 billion Euro, or 296 million Euro per year. Adaptation to changing river discharge conditions will provide a reduction of losses, in the order of 23 billion Euro over the long term and 11 billion Euro over the medium term. Over the short-term period (2014-2030) adaption will reduce losses by 1.7 billion Euro from the around 5 billion expected.

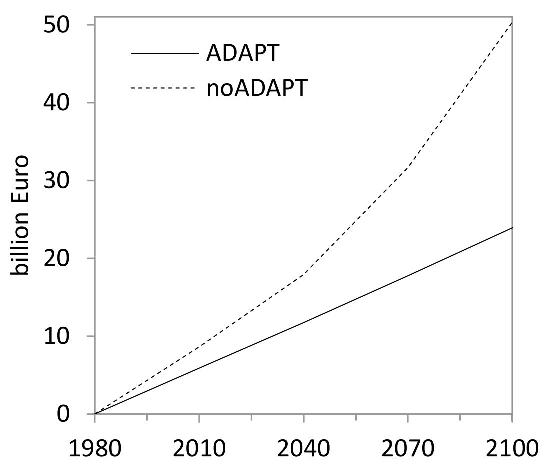

Figure 4: Ensemble-based average aggregated losses (in billion Euro) over the period 1980-2100, under the two adaptation scenarios.

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 (Rose et al. 2007; Hallegatte 2008; Rose and Wei 2013; 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) (Feyen et al. 2012; Rojas et al. 2013). Our results show that the aggregated ensemble-based EAOL increases from 164 million Euro/year to 204 million Euro/year by the end of the century under the WA scenario and to 624 under the WOA scenario (undiscounted 2004 prices). 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. In absolute terms (and without adaptation) the largest part of losses are shared amongst (in order of scale): Lombardy, Veneto, Trentino Alto Adige, Tuscany and Piedmont.

Unfortunately 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). 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 (Esposito et al. 2004), which is extremely high in this region and not represented in our model.

5. CONCLUSION AND POLICY IMPLICATIONS

In this paper we apply the physical drivers of risk (exposure and hazard) used by Rojas et al (2013) to a regionally calibrated global CGE model (R-CGE) to estimate EAOL per region and Italy as a whole. We calculate current and future EAOLs for the period 1980-2100 under 12 climate models. We consider two DRM scenarios, with and without adaptation to changing river discharge conditions. With adaptation the current ensemble-based aggregated EAOL increase by the end of the century of 25 percent, while without adaptation they are projected to increase fourfold.

Considering the limitation of our study to changing river discharge conditions, disregarding socio-economic changes and increasing exposure of economic activities, 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. In Italy this is further reinforced by the undergoing National Climate Change Adaptation Strategy (Castellari et al. 2014) and by the efforts of local agencies for water management River Basin Authorities (AdBPo, Piano di Bilancio). 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 (EC/2007/60), 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. In these terms, the outcomes of this work provide evidence about the need of DRM policies, those specific development surely require further investigations particularly on the cost-side of adaptation. Some authors estimated a cost-benefit ratio of 1 to 4 for flood risk mitigation interventions (Rojas et al. 2013). However, because of the site specific characteristics of each intervention, this study does not account for costs of adaptation, which deserves further and extensive research.

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7. APPENDIX

Table 2: R-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

Table 3: matching of Corine Land Cover (2000) classes to the 14 CGE economic sectors of the R-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

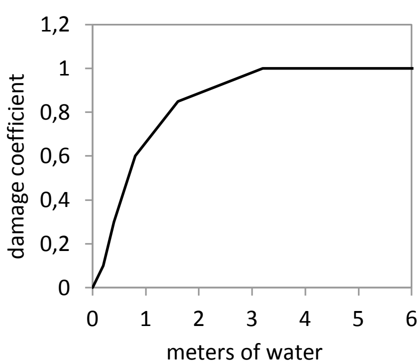

Figure 5: the water depth-duration curve of productivity loss considered in this study.

NUTS code	Name	Prot. Std.
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

Table 4: 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.

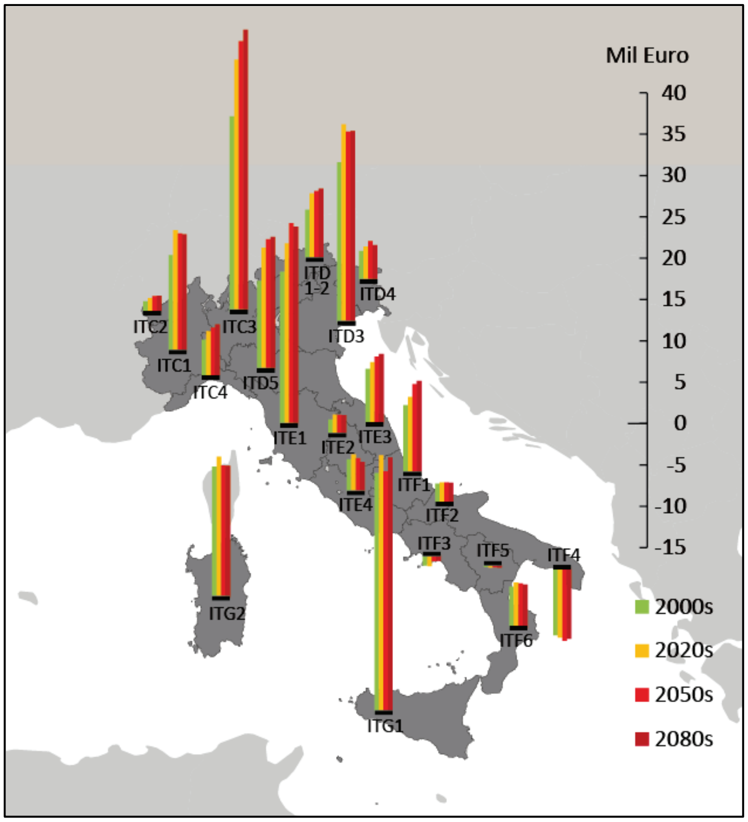

Figure 6: Expected annual output losses per region: ensemble-based average (in million Euro, constant 2004 prices) for the flood protection standards based on heterogeneous FPS (Jongman et al. 2014). Negative values represent gains (ITF3, ITF4, ITF5).

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

Table 5: EAOL per region and Italy as a whole under the two DRM scenarios. The ensemble-based average (in million Euro, constant 2004 prices) are based on heterogeneous FPS. Negative values represent gains if monetary values (e.g. ITF3, ITF4, ITF5) and decreases if in percentage. (*) In Campania, the EAOL under the WA scenario is negative (i.e. a gain), while under WOA the EAOL is positive (a loss).

Table 6 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

CGE models overview and the R-CGE model

In general, 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 firms use the primary factors to produce goods and services, i.e. land, capital, labour and natural resources (fully employed), which are owned by the household and are fixed in supply. Consumers maximize utility, firms maximize profit and the equilibrium in the market system (perfectly competitive) is achieved when the demands of buyers match the supplies of sellers at prevailing prices in every market simultaneously. 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 that 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), allowing for flexibilities in the supply side 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) overcomes this problem, providing an economic analysis at higher resolution. It is important to highlight that, compared to standard global CGE models (e.g. GTAP), we consider a recovery economy 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. 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. We refer the reader to Standardi et al. (2014) and Carrera et al. (2015) for the calibration of the model and the description of the CES (constant elasticity of substitution) and CET (Constant Elasticity of Transformation) functions.