Climate change and critical infrastructure – floods

Georgios Marios Karagiannis

Zehra Irem Turksezer

Lorenzo Alfieri

Luc Feyen

Elisabeth Krausmann

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Contact information
Name: Elisabeth Krausmann
Address: Joint Research Centre, Via Enrico Fermi 2749, 21027 Ispra (VA), Italy
Email: elisabeth.krausmann@ec.europa.eu

JRC Science Hub
https://ec.europa.eu/jrc

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Abstract
This study investigates the change in the level of risk to critical infrastructure due to the impact of climate change on the frequency and severity of floods. We implement a case study focused on the power grid to demonstrate the methodology. The consideration of the power outage substantially changes the estimated losses from the flood scenario. The economic losses due to the interruption of the daily economic activity are 6 to 8 times greater if the power outage outside the inundated area is taken into consideration. In addition, the losses from the disruption of daily economic activity far outweigh the cost of transmission asset repairs, and amount to 99% of the total cost.

Contents

Executive summary

Critical infrastructures are the backbone of modern society and provide for many of the essential services that serve as the foundation of European economy. The risk environment facing critical infrastructure has evolved considerably over the last 20 years. For example, climate change is increasing the frequency and severity of hydro-meteorological hazards, such as floods and storms, and may warrant a re-prioritization of critical infrastructure resilience in government agendas.

Adaptation to climate change relies on critical infrastructure resilience, and both require a better understanding of the hazards critical infrastructures are exposed to. The purpose of this study was to develop and present a methodology to investigate the impact of climate change on the risk posed by floods to critical infrastructure. More specifically, the study objectives were 1) to understand how losses for a current 100-year flood scenario change if infrastructure ripple effects outside the inundated area are considered and 2) how climate change will affect future risk levels. A case study was conducted in a large urban center in Western Europe, focusing on the power grid as a first step. The scope of this study is limited to demonstrating the feasibility of the methodology and inductively drawing preliminary conclusions regarding the impact of floods on critical infrastructure given climate change conditions.

Our approach combines a future projection of the recurrence interval of selected flood scenarios and the assessment of the estimated losses incurred by critical infrastructure and resulting from the disruption of daily economic activity. The projected probability of a current 100-year flood scenario in the case study area was derived from the pan-European flood risk assessment under high-end climate scenarios conducted by the European Commission's Joint Research Centre. Ensemble projections indicate that flood hazard may increase in the study area, yet there is considerable climate uncertainty around these central estimates. To cover the range of possible future flood hazard conditions, we tested different climate change scenarios to understand the sensitivity of the study to different climate model outcomes.

Flood hazard scenarios were analyzed using JRC's Flood Hazard Maps. The analysis included the potential damage to critical electric infrastructure facilities and assets, and the losses resulting from the disruption of the daily economic activity in the area affected by the power outage caused by the inundation or preemptive shut down of the electric substations located in the inundation zone. This area can be larger than the inundation zone.

For the selected case-study region, the application of the presented methodology showed that, despite their low severity, floods with a low return period yield the highest level of economic risk. In addition, the economic losses due to the interruption of the daily economic activity are 6 to 8 times greater if the power outage is taken into consideration than if only the area affected by the flood is considered. In addition, the losses from the loss of daily economic activity far outweigh the cost of transmission asset repairs, and amount to 99% of the total cost. Of the remaining less than 1%, the cost of substation damage is 10 times greater than damage to transmission. The severity of the flood and power outage combined for the 100-year flood is more than double that of the 10-year scenario. The increase results mainly from the inundation of a considerably larger area in the 100-year scenario and from the assumption of a longer duration of the flood and power outage. In other words, the 100-year flood affects more businesses and for a longer time. On the other hand, the total economic cost increases by only about 10% between the 100-year and 200-year scenario. The increase is due to the combination of greater water depths at all power grid assets and a slightly wider area affected by the flood

The methodology can be readily extended to other critical infrastructure sectors, provided the availability of depth-damage functions. It may also be extended to other hazards, as long as there exist statistical correlations between the intensity of the hazard and the level of damage. For example, fragility functions are available for earthquakes and hurricanes. Possibilities for future research include the improvement of depth-damage functions.

1 Introduction

Critical infrastructures are the backbone of modern society and provide for many of the essential services that serve as the foundation of European economy. They include *systems or assets which are essential for the maintenance of vital societal functions, health, safety, security, and economic or social well-being of people*[1]. The safety and security of critical infrastructure is an indispensable prerequisite for community resilience. The disruption of critical infrastructure may be caused by natural hazards, technological accidents, malicious attacks or other causes. Although it is unlikely that it may result in widespread death or injury, the loss of critical infrastructure systems can debilitate the economy, health and security of a community or nation. Damage to critical infrastructure systems caused by natural hazards may slow down response and recovery, and increase the cost of reconstruction.

The risk environment facing critical infrastructure has evolved considerably over the last 20 years. Initially directed predominantly at natural hazards, the focus of critical infrastructure protection has progressively shifted to new threats, such as terrorist attacks, including the possibility of terrorists using weapons of mass destruction (WMD) and Chemical-Biological-Radiological-Nuclear-Explosive (CBRNE) agents, as well as cyber risks. However, climate change is increasing the frequency and severity of hydro-meteorological hazards and may warrant a re-prioritization of critical infrastructure resilience in government agendas. Recent studies (Forzieri et al., 2017) have pointed out that the impact of climate change on critical infrastructure may increase substantially in the coming decades.

Adaptation to climate change relies on critical infrastructure resilience, and both require a better understanding of the risk environment facing critical infrastructure. The purpose of this study was to develop and present a methodology to investigate the impact of climate change on the risk posed by floods to critical infrastructure. Climate change is expected to increase the frequency and severity of floods throughout Europe (Alfieri et al., 2015a). Our approach combines a future projection of the recurrence interval of selected flood scenarios and the assessment of the estimated losses incurred to critical infrastructure and resulting from the disruption of daily economic activity.

A case study was conducted to demonstrate the methodology in a large urban area in Western Europe, focusing on critical electric infrastructure as a first step. The scope of this study is limited to demonstrating the feasibility of the methodology and inductively drawing preliminary conclusions regarding the impact of floods on critical infrastructure given climate change conditions. It is not intended to supplement, replace or challenge existing risk assessment and management plans prepared by Member States. Among all critical infrastructure sectors, electric power is a cornerstone of modern economies. Electricity is ubiquitous in the daily lives of European citizens and spans across all sectors of the European economy. In addition, all critical infrastructure systems depend, to a greater or lesser extent, on the reliable delivery of electricity. Long-term power outages can slow down disaster recovery efforts and severely disrupt the economy of affected communities (Petermann et al., 2011; Karagiannis et al., 2017).

This report is structured in six chapters. Chapter 2 outlines the European policies regarding electric power supply security, the impact of floods on critical electric infrastructure and current knowledge about the impact of climate change on floods. Chapter 3 discusses the methodology, while chapter 4 presents the results of the case study. Chapter 5 is a discussion of the results, focusing on the implications for flood risk management, the limitations, as well as the possibility for extending the methodology. Last, chapter 6 summarizes our findings.

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[1] Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection (OJ L 345/75, 23.12.2008, p. 75-82).

2 Climate change, floods and critical electric infrastructure

Floods affect more people than any other hazard in Europe. 30 out of the 34 countries participating in the Union Civil Protection Mechanism (UCPM) have included floods in their national risk assessment. Riverine floods are mostly prevalent in Central, Eastern and Northern European Countries, while flash floods are common in Southern European countries. Climate change is expected to change pattern of floods in Europe. The frequency and severity of floods is expected to rise in most countries, but would also decrease in some. Of the 30 Member States which have included flood scenarios in their NRAs, 10 have considered that floods may disrupt critical infrastructure. In addition to the loss of critical infrastructure as a secondary effect of identified hazards and threats, 20 NRAs include scenarios of long-term power outage (EC, 2017; Krausmann et al., 2016).

In recent years, the losses from floods in Europe have increased considerably, due to an increase of the economic activity in flood zones and of heavy rainfall in parts of Europe (EEA, 2016). The electric power grid is particularly vulnerable to floods, and power outages are a frequent consequence of severe floods (Karagiannis et al., 2017). This chapter briefly outlines the policy and regulatory framework regarding electricity, floods and climate change in the European Union, the impact of floods on critical electric infrastructure and the likely effects of climate change on the frequency and severity of floods in Europe.

2.1 Policy and regulation

2.1.1 Electricity

Electricity critical infrastructure assets and facilities are owned by public and private entities. The electric power subsector faces a paradigm change to a much more horizontal system where end-consumers will play a much more active role, in accordance with the EC energy policy as expressed in the Clean Energy Package for all Europeans.

At the EU level, electricity risk reduction and crisis management are scattered over different legal acts. At the pan-European level, the European Network of Transmission System Operators for Electricity (ENTSO-E) produces seasonal outlooks according to the requirements of Article 8 of the Electricity Regulation[2]. These outlooks explore the main risks identified, but are mainly focused on generation adequacy and do not fully account for floods or other natural hazards. At the Member State level, risk preparedness is only implicitly set in Article 4 of the Electricity Directive[3] and Article 7 of the Security of Supply (SoS) Directive[4] which impose the general obligation to Member States to monitor security of supply and to publish every two years a report outlining their findings, as well as any measures taken or envisaged to address them. The success, especially in terms of harmonization, of the above legal frameworks is rather debatable (Karagiannis et al., 2017).

Risk preparedness in the Internal Energy Market is an ongoing regulatory effort. Three network codes are of main importance on the subject: the CACM Guideline[5], the SO

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[2] Regulation (EC) No 714/2009 of the European Parliament and the Council of 13 July 2009 on conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003 (OJ L 51/15, 14.8.2009, p. 15-35).
[3] Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC (OJ L 211/55, 14.8.2009, p. 55-93).
[4] Directive 2005/89/EC of the European Parliament and of the Council of 18 January 2006 concerning measures to safeguard security of electricity supply and infrastructure investment (OJ L 33/22, 4.2.2006, p. 22-27).
[5] Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management (OJ L 197/24, 25.7.2015, p. 24-72).

Guideline[6], both already in force, and the Network Code on Emergency & Restoration[7], still in Comitology. Even though these network codes contribute to the creation of a harmonized framework for assessing security of supply and coordinate remedial actions in both emergency and system recovery situations, they still address risks mainly within the context of generation adequacy, and are not a full vulnerability analysis. The European Commission has proposed a Regulation on risk-preparedness[8] to address the regulatory gap in the context of the Clean Energy for all Europeans package. The Regulation aims for the creation of a general legislative framework for the prevention, preparation for and management of electricity crisis situations (Karagiannis et al., 2017).

2.1.2 Disaster risk management

Several policy areas related to disaster risk management address, directly or indirectly, the resilience of the power grid against floods and other natural hazards. First, National Risk Assessments, required by Article 6 of the Union Civil Protection Mechanism Decision[9], should consider the impact of hazards on critical infrastructure. The Floods Directive[10] requires Member States to develop flood-specific risk analyses taking into account scenarios with different return periods. The Water Framework Directive[11] advances the protection of water resources as a mitigation measure against floods and droughts. The Seveso III Directive[12] explicitly compels industrial facility operators to consider natural hazards as initiating events in the analysis of the risk from hazardous materials releases. The European Critical Infrastructure (ECI) Directive[13], focusing on energy and transport, explicitly requires Member States to designate ECIs based on the potential impact of the disruption of critical infrastructure systems, expressed in terms of casualties, and economic and public effects.

2.1.3 Climate change

Energy is at the center of the EU's climate action. Critical infrastructure resilience against natural hazards is one of the three objectives of the EU Adaptation Strategy[14]. Hydro-meteorological hazards (such as floods and storms) cause direct damage to transmission and distribution networks. Older regional distribution grids are particularly vulnerable to natural hazards. Floods can also adversely affect electricity generation capabilities. The power grid is also likely to be challenged from changing demand patterns (EC, 2011).

Resilience can be built into infrastructure by designing new facilities and assets with future climate hazards in mind and by retrofitting existing assets to withstand increased forces or

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[6] Draft Commission Regulation establishing a guideline on electricity transmission system operation (final), https://ec.europa.eu/energy/sites/ener/files/documents/SystemOperationGuideline%20final%28provisional%2904052016.pdf (accessed July 14, 2017)

[7] Draft Commission Regulation establishing a network code on electricity emergency and restoration (final), https://ec.europa.eu/energy/sites/ener/files/documents/nc_er_ener_vs_13_ecbc_on_24_25-10-2016finalasvotedfor_publication.pdf (accessed July 14, 2017)

[8] Proposal for a Regulation of the European Parliament and of the Council on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC (COM/2016/0862 final – 2016/0377 COD), http://eur-lex.europa.eu/resource.html?uri=cellar:1d8d2670-b7b2-11e6-9e3c-01aa75ed71a1.0001.02/DOC_1&format=PDF (accessed July 14, 2017)

[9] Decision No 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism (OJ L 347/924, 20.12.2013, p. 924–947)

[10] Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (OJ L 288/27, 6.11.2007, p. 27–34)

[11] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (OJ L 327/1, 22.12.2000, p. 1–73)

[12] Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC (OJ L 197/1, 24.7.2012, p. 1–37)

[13] Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection (OJ L 345/75, 23.12.2008, p. 75-82)

[14] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: An EU Strategy on adaptation to climate change (COM/2013/0216 final), http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013DC0216 (accessed December 1, 2017)

more frequent occurrences of natural hazards. Climate projections need to be used to guide analyses of the vulnerability of interconnected grids to the estimated levels of hazards. These assessments should then be used to craft and execute cross-disciplinary strategies, combining land use, engineering and organizational measures (EC, 2013).

2.2 Impact of floods on critical electric infrastructure

Floods cause widespread damage to the power grid assets and are commonly associated with power outages. In a recent study of 20 floods caused by heavy rainfall or hurricanes, electricity was interrupted in 100% of the cases. Power was restored progressively, with the blackout generally lasting from less than 24 hours to one week. Hurricanes were associated with longer blackouts which exceeded one month, but the fraction of the damage caused by floodwaters was difficult to determine (Karagiannis et al., 2017). The following sections outline how floods affect electricity infrastructure, flood mitigation options for electric utilities and courses of action for emergency response.

2.2.1 Flood damage and mitigation

Floods affect all assets which come into contact with water. Inundated equipment can fail catastrophically if under tension. In addition, large quantities of water and mud may be trapped in inundated circuit breakers, transformer parts, control house equipment, and metallic switchgear, requiring delicate, costly and time-consuming cleanup and repairs. The level of damage, and therefore the cost and duration of required repairs has been found to increase with the water depth and the duration of the inundation (Karagiannis et al., 2017).

Because of their ubiquity and high concentration of sensitive equipment, substations are at increased risk from floods. It is generally accepted that the restoration of a flooded substation takes much longer than the repair of a downed power line damaged by ice or wind (Abi-Samra, 2010). Flood mitigation strategies, such as locating the substation above projected flood levels, levee protection and elevating critical equipment, have been effective in reducing the damage to critical substation equipment (Karagiannis et al., 2017). Burying distribution substations has been considered as a hazard mitigation measure in urban areas, but has proven to be costly, time-consuming and ineffective. Abi-Samra (2013) reports that underground assets have been washed away during hurricanes and are reportedly prone to frequent flooding.

Buoyancy, hydrostatic and hydrodynamic loads, and debris impact typically contribute to flood-generated structural damage to technological systems (Krausmann et al., 2011). Transmission towers are more vulnerable to this type of damage than substations. Landslides and soil erosion secondary to floods or heavy rainfall may severely undermine the foundations of transmission towers. On the other hand, structural damage is limited and not critical to the duration of the power outage (Karagiannis et al., 2017).

2.2.2 Emergency response

Because of the devastating effects of water intrusion to electrified substation equipment, preemptively shutting down power to vulnerable substations located in the flood zone is a very popular course of action with electric utilities facing an imminent flood (Karagiannis et al., 2017). Its advantage is that it prevents the catastrophic, often explosive, damage caused when water comes into contact with live equipment.

The drawback of this course of action is that is results in longer blackouts extending over wider areas. Because substations typically serve the area surrounding them in all directions, when a substation is shut down, the outage may extend to areas otherwise unaffected by the flood. In a few rare instances, substations have been preemptively shut down, but ended up not being inundated. Furthermore, many areas may be without power longer than being underwater, especially if the river spills over from its banks onto the adjacent floodplain. In this case, substations are typically inundated before the area they service is entirely under water. As floodwaters recede, substations may remain immersed

while part of the area they service is no longer inundated. On the other hand, if the river overflow is associated with a sharp rise of the aquifer, which is a typical case in floods occurring over permeable soils and/or caused by heavy rainfall, the substation may be inundated more or less simultaneously with the surrounding area.

Despite causing blackouts that last longer and extend over a larger area, the preemptive shut down strategy is effective because it prevents catastrophic damage and therefore shortens the repair time. However, even with the preventive shut down, the time needed to conduct delicate repairs may prolong the blackout. Sensitive inundated equipment will have to be disassembled and cleaned, while some items may be damaged beyond repair. In addition, many types of repairs cannot start until the waters recede, adding further to the duration of the power outage for many areas. Repairs may also be delayed because of poor access to affected substations and transmission towers, resulting from inundated roads, railway tracks and bridges, as well as traffic congestion. Last, telecommunications outages, either due to inundation of equipment or secondary to the power blackout, can also prolong the recovery phase (Karagiannis et al., 2017).

2.3 Impact of climate change on the flood hazard in Europe

A pan-European flood hazard assessment by Alfieri et al. (2015b) indicates that extreme river flows are projected to rise significantly in most of Europe. This is shown in Table 1 that reports the results of the frequency analysis of extreme peak flow events above a 100-year return period (referred to as f_{100}), aggregated at country level. The predominance of positive changes in f_{100} means that in all countries there will be an increase in frequency of severe flood events. Such an analysis is of particular interest, given that the average protection level of the European river network is of the same magnitude (Rojas et al., 2013), with some obvious differences among different countries and river basins (Jongman et al., 2014). In other words, a substantial increase in the frequency of peak flows below the protection level is likely to have a lower impact, in terms of critical infrastructures potentially affected and economic losses, in comparison to a small but significant change in extreme events overtopping protection structures and causing settled areas to be inundated by the flood flow. Values shown in Table 1 were obtained by counting the average frequency of occurrence in all grid points of the river network within each country. The statistical significance of the estimated change in the ensemble mean was tested with a two-proportion z test. A stringent p value of 1‰ is chosen as threshold for significance, to compensate for the autocorrelation of extreme events in neighbouring grid points along the drainage direction. In addition, this issue is mitigated by the use of an ensemble of seven independent climate projections. Note that no flood hazard was computed for Cyprus and Malta because the river network in these countries is below the minimum threshold considered in the analysis.

Table 1. Mean annual exceedance frequency of the 100-year return period peak flow for different European countries and percentage change between the baseline and the future time slices ([1]).

Country	f_{100}			Δf_{100}	
	baseline	2021-2050	2071-2100	2021-2050	2071-2100
Austria	0.0067	0.0223	0.0316	231%	369%
Belgium	0.0102	0.0344	0.0519	235%	407%
Belarus	0.0083	0.0152	0.0157	83%	90%
Bosnia - Herzegovina	0.0096	0.0211	0.0302	121%	216%
Bulgaria	0.0159	0.0292	0.0324	84%	104%
Croatia	0.0062	0.0165	0.0267	165%	328%
Cyprus	0.0000	0.0000	0.0000	0%	0%
Czech Republic	0.0140	0.0199	0.0246	42%	76%
Denmark	0.0179	0.0228	0.0377	*28%*	111%
Estonia	0.0025	0.0069	0.0118	179%	379%

Finland	0.0031	0.0030	0.0034	*-4%*	*11%*
France	0.0094	0.0235	0.0334	150%	256%
FYROM	0.0120	0.0204	0.0464	69%	285%
Germany	0.0115	0.0235	0.0282	105%	146%
Greece	0.0113	0.0242	0.0410	113%	262%
Hungary	0.0087	0.0222	0.0236	153%	170%
Ireland	0.0086	0.0211	0.0494	147%	477%
Iceland	0.0020	0.0100	0.0235	390%	1050%
Italy	0.0126	0.0241	0.0483	92%	284%
Kosovo	0.0088	0.0443	0.0512	405%	484%
Lithuania	0.0078	0.0131	0.0122	66%	55%
Luxemburg	0.0058	0.0201	0.0194	247%	235%
Latvia	0.0054	0.0163	0.0192	202%	255%
Malta	0.0000	0.0000	0.0000	0%	0%
Moldova	0.0203	0.0402	0.0310	98%	53%
Montenegro	0.0089	0.0200	0.0388	125%	335%
The Netherlands	0.0090	0.0358	0.0511	296%	465%
Norway	0.0027	0.0086	0.0091	215%	233%
Poland	0.0125	0.0268	0.0261	114%	109%
Portugal	0.0074	0.0115	0.0237	55%	220%
Romania	0.0088	0.0224	0.0266	154%	201%
Serbia	0.0091	0.0275	0.0374	203%	313%
Slovenia	0.0061	0.0230	0.0365	279%	501%
Slovakia	0.0050	0.0153	0.0144	206%	190%
Sweden	0.0029	0.0062	0.0093	118%	224%
Spain	0.0090	0.0185	0.0286	106%	218%
Switzerland	0.0036	0.0122	0.0223	238%	517%
United Kingdom	0.0120	0.0216	0.0410	81%	242%
Europe	0.0080	0.0204	0.0320	113%	234%

(^{1}) Changes in italic are not significant at 1‰.

3 Methodology

This study estimates the change in the level of risk posed to critical infrastructure resulting from the impact of climate change on the frequency of floods in a selected area in Europe. Disaster risk results from the probability of occurrence of a flood and the severity of the event. The probability may be expressed either qualitatively or quantitatively, depending on the level of knowledge available about each hazard. The severity is expressed in terms of the expected deaths and injuries, damage to property, disruption of critical infrastructure, and social consequences (Agius et al., 2017). The scenario-based approach is a popular disaster risk analysis methodology and is highly appropriate for the analysis of hazards for which detailed statistical information is available. Here, the change in the level of risk in this study is estimated by the change in the probability and the severity of floods (Figure 1).

3.1 Probability of occurrence

The probability of occurrence of a flood scenario is quantified by its recurrence interval[15]. Although several disaster risk studies typically analyze several flood scenarios, the 100-year flood is the standard reference in hazard mitigation and emergency planning.

Climate change is expected to change the frequency of floods in Europe. For any given river, the probability of occurrence of what is currently the 100-year flood could be increased or decreased. Using the statistical and quantitative analysis approach discussed in Alfieri et al. (2015a), we derive the return period of the baseline 100-year flood in three future time slices, i.e. 2020, 2050 and 2080, based on the EURO-CORDEX climate scenarios.

3.2 Loss estimation

Each scenario is analyzed to determine the consequences of the flood on the affected communities. The potential losses are a function of the intensity of the hazard (in this case, the water depth and the duration of the incident) and the exposure of people and economic activities to that hazard. Because the objective of this study is to determine the impact on critical infrastructure, the loss estimation focuses primarily on the economic losses resulting from the damage incurred to electric utilities in the affected area. The approach is illustrated on the left side of Figure 2 and further detailed in section 3.2.1.

In addition, we estimate the impact to the local economy resulting from the combination of the pre-emptive shutdown of substations located in the flood zone and the time required to conduct repairs once the flood has subsided. The process is illustrated on the right side of Figure 1 and detailed in section 3.2.2.

The underlying assumption is that the power outage associated with the flood does not cause additional casualties, injuries, or loss of property. This is likely to be an underestimation, because a prolonged power outage is expected to undermine disaster response capabilities, disrupt healthcare facilities, render heating and air-conditioning systems inoperable, generate traffic jams and contribute to traffic accidents (Petermann et al., 2011; Karagiannis et al., 2017). However, existing methodologies cannot grasp the secondary effects of power outages, as these depend to a large extent on additional parameters, such as local climate and weather, prior disaster response capabilities, and public health before the flood.

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[15] The recurrence interval is an estimate of the likelihood of occurrence of an event. It is defined as the average number of years between floods of a certain size. The actual number of years between floods of any given size varies a lot. A common misconception about the 100-year flood is that it is likely to happen only once in 100 years. In reality, a 100-year flood is the flood which has a 1% annual exceedance probability, that is, a 1% chance of occurring every year. In other words, it is possible for the 100-year flood to occur two or more times per year.

Figure 1. Concept diagram of the change in risk level
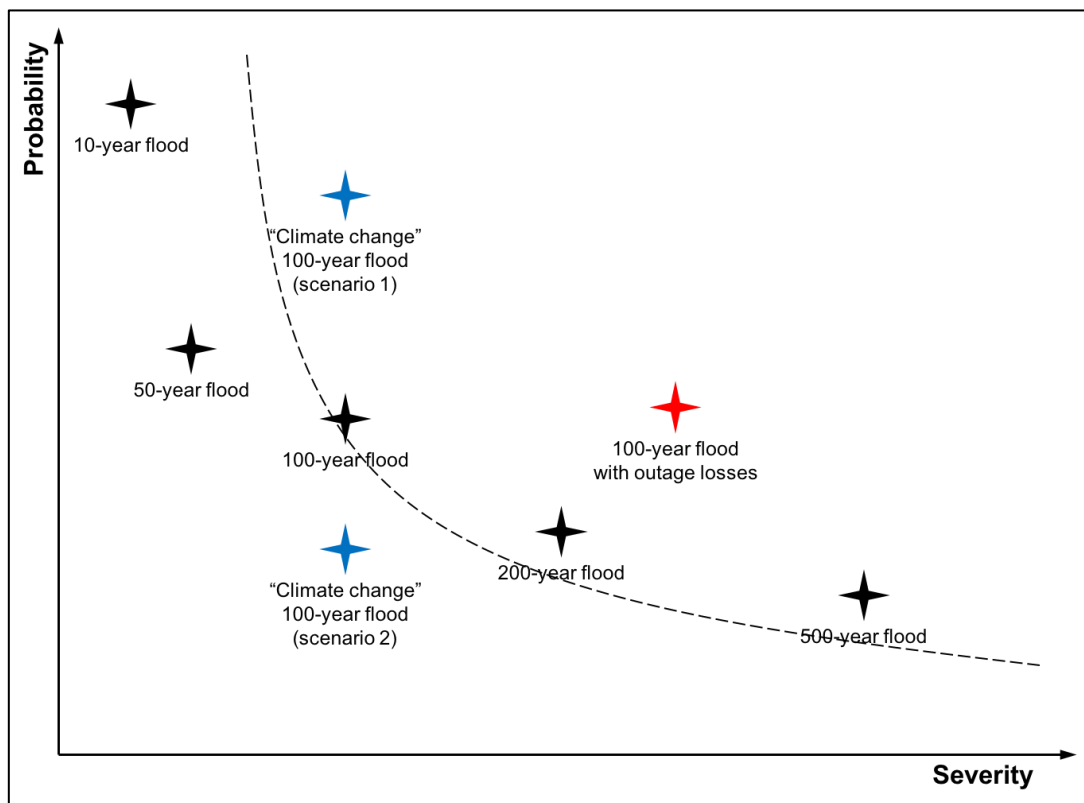
Figure 2. Loss estimation approach
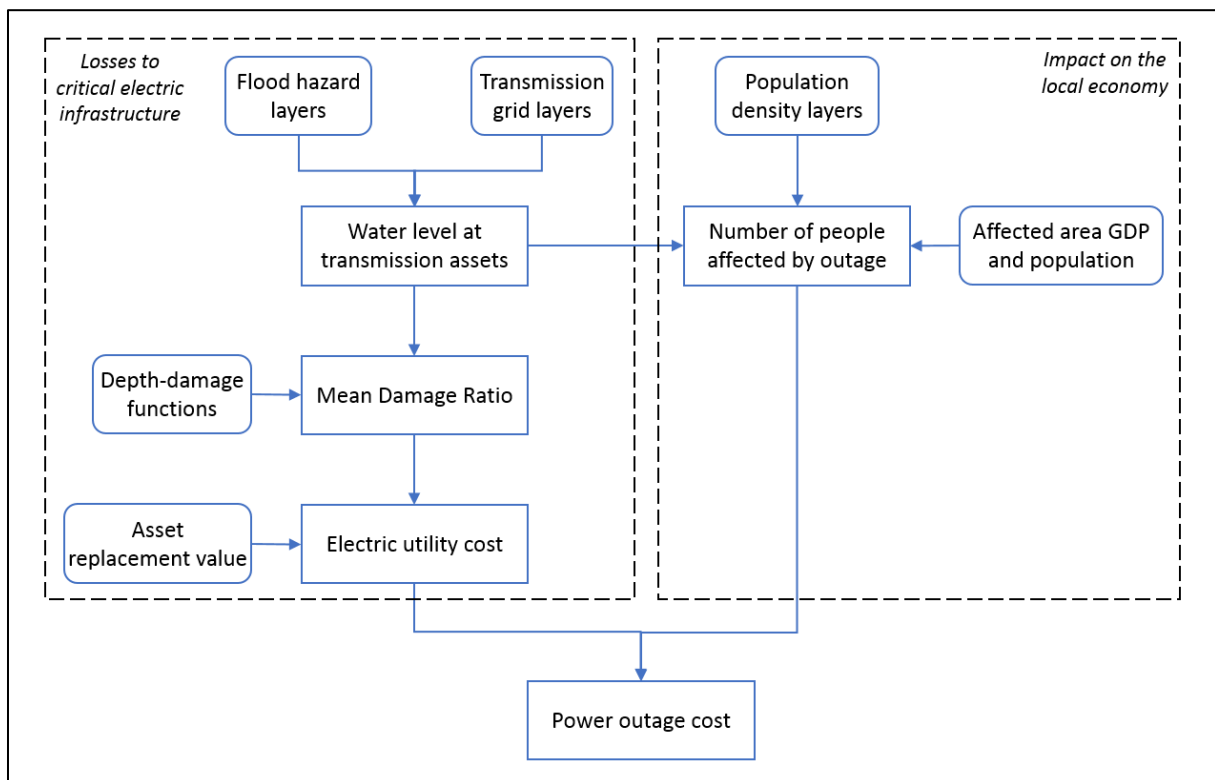
3.2.1 Losses to critical electric infrastructure

The cost incurred by the damage to inundated power grid assets is estimated by the projected flood depth combined with appropriate damage functions (Figure 2, left side). First, we determine the exposure of power grid components to flood hazards. Flood hazard maps are combined with geospatial data layers of the transmission grid to derive the components of the power grid (power plants, substations, transmission towers and lines) located in the inundation zone. This exercise also determines the flood depth to which each of these facilities or structures are exposed. It is assumed that warning of the impending flood is received early enough for the TSO and/or electric utility to switch off power to the unprotected power plants and substations located in the inundation zone.

The exposure geospatial data layer is combined with depth-damage functions to derive the cost of repairs of the inundated components. Mean damage functions relate the hazard intensity (in this case, water depth) to the mean damage ratio of a facility or asset, which is expressed as the expected value of the ratio between an asset's repair cost over its replacement value (Mahdyiar and Porter, 2005; Dutta, Herath & Musiake, 2006):

$$Mean\ damage\ ratio\ (MDR) = E\left[\frac{Repair\ cost}{Replacement\ value}\right]$$

The MDR is expressed as a percentage of the replacement value and can theoretically be greater than 1, because the repair cost of a severely damaged facility or asset may exceed its replacement value. The exposed facilities and assets are grouped in several categories based on their type and similarities in expected loss (Scawthorn et al., 2006). Damage to each category of equipment is estimated with a separate damage function. Therefore, the total damage is derived from the water depth and replacement value of each facility or asset:

$$Total\ Repair\ Cost\ (TRC) = \sum_{j=1}^{m}\sum_{i=1}^{n} f_j(x_{ij}) \cdot RV_{ij}$$

where:

— $i = 1, 2, …, n$: facilities or assets belonging to each category

— $j = 1, 2, …, m$: categories of facilities or assets

— RV_{ij}: replacement value of each facility or asset i (of each category j)

— x_{ij}: water depth at each facility i (of each category j)

— $f_j(x_{ij})$: depth-damage function of facility or asset category.

3.2.2 Impact on the local economy

The effect of the power outage on the local economy is approximated by the economic activity that is interrupted, on a per capita basis (Figure 2, right side). First, we determine the number of people affected by the flood and outage together. When a transmission substation is switched off, customers connected to that substation will lose power, unless the TSO can reroute power from another location. The area affected by the loss of power to a transmission substation is approximated by its influence zone, which is derived using Voronoi/Thiessen polygons (Sen, 2016; Longley et al., 2015). The combination of the affected area with a population density map yields the number of people affected by the outage. To this fraction of the jurisdiction's population, we add the segment in the inundated area but outside the area affected by the power outage.

Voronoi/Thiessen polygons effectively approximate the influence zone of each substation, but they come with two disadvantages. First, the influence zone determined by the Thiessen polygon may not correspond to the actual area receiving power from the substation. In other words, the distribution network may be built in such a way that each client does not get power from their nearest substation. Second, the use of Thiessen polygons assumes that each client may receive electricity from only one substation. If that

substation is shut down, then this client loses power until the substation is brought back online. However, each client may be connected to two or more substations, and redundancies are often built into the transmission grid (and more often in the distribution grid), which allow TSOs to switch to a different source when a substation is shut down.

The business cost is the sum of the costs incurred by the outage and the flood. The business losses from the outage are approximated by the daily economic activity that is interrupted (Zimmerman et al., 2005). The outage stops all business in the affected area until power is back online. To that we add the cost from the interruption of the daily economic activity exposed to the flood but not the power outage. In both cases, costs are estimated on a per capita basis:

$$Business\ Cost\ (BC) = \frac{GDP \cdot \left(t_{out} \cdot P_{out} + t_f \cdot P_{f\prime}\right)}{365 \cdot P_{tot}}$$

where:

— GDP: the Gross Domestic Product of the jurisdiction under review (e.g. a city)[16]

— t_{out}: the estimated duration of the outage (in days).

— P_{out}: the population affected by the outage.

— t_f: the estimated duration of the flood episode (in days).

— $P_{f\prime}$: the population in the inundated area but outside the area affected by the power outage.

— P_{tot}: the jurisdiction's entire population.

This formulation is based on three underlying assumptions. The first is that the power outage lasts longer than the flood episode itself, therefore the first term in the numerator of the Business Cost (BC) formulation is dominated by the duration of the outage and not of the flood episode. This is a realistic hypothesis, because electric utility assets located in the flood zone are shut down before the flood and they are switched back on after the waters have receded. The second assumption is that the duration of the outage is the same throughout the affected area. This could be an overestimation, because power is restored progressively as repairs are made (Karagiannis et al., 2017).

The third assumption is that the local economic activity is homogeneously distributed throughout the flood affected area. This could be an underestimation or overestimation of the business cost, depending on the locus of economic activities. For instance, if business is more concentrated near the river, then the estimated business cost will be lower than the actual one. On the other hand, if local businesses are located outside the flood zone and/or the area affected by the outage, then the estimated cost would constitute an overestimation.

3.2.3 Losses from the flood alone

The combined impact of the flood and the outage is compared with the estimated losses if only the flood was considered. In this case, the economic impact is approximated by the interruption of the daily economic activity exposed to the flood (Zimmerman et al., 2005). Assuming the inundated area is evacuated for the duration of the flood, all business in that area is interrupted. Therefore, the economic cost is estimated on a per capita basis:

$$Flood\ Cost\ (FC) = \frac{GDP \cdot t_f \cdot P_f}{365 \cdot P_{tot}}$$

where:

— GDP: the Gross Domestic Product of the jurisdiction under review.

([16]) If the jurisdiction GDP is not available, it may be estimated by dividing the country's GDP by its population, and then multiplying the result by the population of the jurisdiction under review.

— t_f: the estimated duration of the flood episode (in days).

— P_f: the population in the inundated area, estimated by the combination of the area with a population density map.

— P_{tot}: the jurisdiction's entire population.

This formulation is based on two assumptions. The first is that the interruption of daily economic activity starts and ends at the same time throughout the entire flood zone. This may be partially true, as the entire flood zone may be evacuated before the flood, within a few hours or a day. However, economic activity is likely to be progressively restored as floodwaters gradually recede. Therefore, this assumption may lead to an overestimation of the losses, in the same way as the combined impact of the flood and outage discussed in section 3.2.2. The second assumption is the same as in the previous case, that the local economic activity is homogeneously distributed throughout the flood affected area.

We compare the level of economic damage due to the disruption of the daily economic activity if the analysis considers the loss from the flood alone, with that which is determined by also considering the power outage. It is again assumed that the power outage does not cause additional casualties, injuries, or loss of property.

3.2.4 Combined impact of the flood and outage

The last step in the loss estimation is the estimation of the combined impact of the flood and outage, which is calculated as the sum of the costs to electric utilities and the impact to the local economy resulting from the flood and the outage:

$$Total\ Cost\ (TC) = TRC + BC$$

3.3 Change in risk level

The level of risk is derived as the expected value of the losses incurred from each scenario (Hickman & Zahn, 1966):

$$Risk\ = E(TC)$$

We analyze the change in the level of risk (expressed in terms of the expected economic losses) caused by the change (increase or decrease) of the probability of occurrence of the 100-year flood scenario because of climate change.

4 Demonstration of the methodology

A case study was used to demonstrate the methodology outlined in section 3. A large metropolitan area in Europe was used as a case study. The following sections outline how the methodology was implemented. Section 4.1 briefly presents the case study site. Section 4.2 discusses the change in the probability of occurrence of the 100-year flood scenario for the area, which was estimated using the methodology discussed in Alfieri et al. (2015a). Section 4.3 describes the impact severity of the flood scenarios, which was approximated by the damage to transmission grid assets and the interruption of the daily economic activity in the area because of the flood and the power outage.

4.1 Case study site

Hazardville (Figure 3) has a population of approximately 1,280,000 and a surface area of 538 km^2. Hazardville is a landlocked area, with no direct access to the sea. It is located at the convergence of two navigable rivers. The two rivers converge inside the historic center of Hazardville, forming a peninsula, which has become a cultural, commercial and administrative part of the city. The topography of Hazardville is relatively flat to the east of one river, and most of modern Hazardville sits there. Hazardville has a humid subtropical climate. The mean temperature ranges from 3.4^{o}C in January to 22.1^{o}C in July. The average annual precipitation is approximately 832 mm, with two peaks in May (approximately 91 mm) and October (98.6 mm). Electricity in the country Hazardville is located in, is managed in accordance with European and national law.

Figure 3. Map of Hazardville
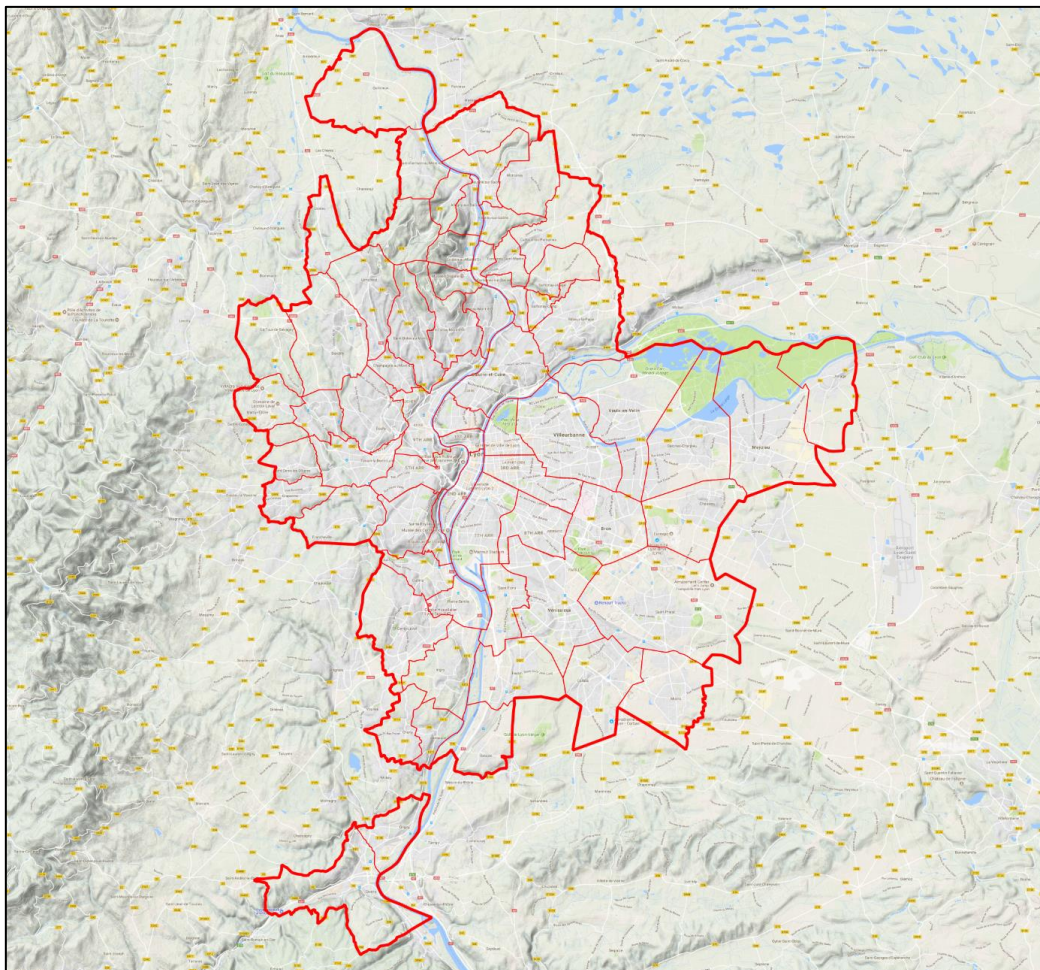
Source: JRC. Background: Google Maps®. Hazardville layers: https://www.data.gouv.fr/fr/ (accessed November 14, 2017)

4.2 Probability

Flood hazard scenarios were analyzed using JRC's Flood Hazard Maps derived at European and global scale (Alfieri et al., 2014; Dottori et al., 2016). These maps have been developed using two-dimensional hydrodynamic models and streamflow data from the European Flood Awareness System (EFAS) and the Global Flood Awareness System (GloFAS). It is noted that these maps may differ from national flood hazard maps, and do not constitute official flood hazard maps. The collection includes European and global flood hazard maps for the 10-year, 20-year, 50-year, 100-year, 200-year and 500-year scenarios. European flood hazard maps are available at 100 m resolution, while the global maps are available at 10 km resolution. In this study, we used the European 10-year (Dottori et al., 2016a), 100-year (Dottori et al., 2016b) and 200-year (Dottori et al., 2016c) flood maps.

In Section 2.2 it was described how climate change may affect the flood hazard in Europe, based on the analysis of Alfieri et al. (2015a). It shows that in the country Hazardville is located in, the frequency of rare events (exemplified by the present 100-year flood) will increase with global warming (See Table 1 in Section 2.2). From the pan-European assessment of Alfieri et al. (2015a) we derived for 3 future time slots the projected recurrence frequency of a present 100-year flood event along the rivers in Hazardville. This is illustrated in Figure 4 and Table 2. The flood hazard projections indicate that today's (baseline) 100-year flood would occur more frequently in the future in Hazardville, similar to the general trend for the country. There is, however, large climate uncertainty in the projected future flood hazard, as can be seen from the range in future recurrence frequencies projected by the different EURO-CORDEX climate realizations. For instance, the recurrence interval of the baseline 100-year scenario could range from 13 years to 170 years by 2080 depending on the selected climate model. The spread increases with time due to the uncertainty in how climate may develop as time proceeds.

Figure 4. Recurrence interval of the 100-year flood scenario for Hazardville based on the EURO-CORDEX climate scenarios
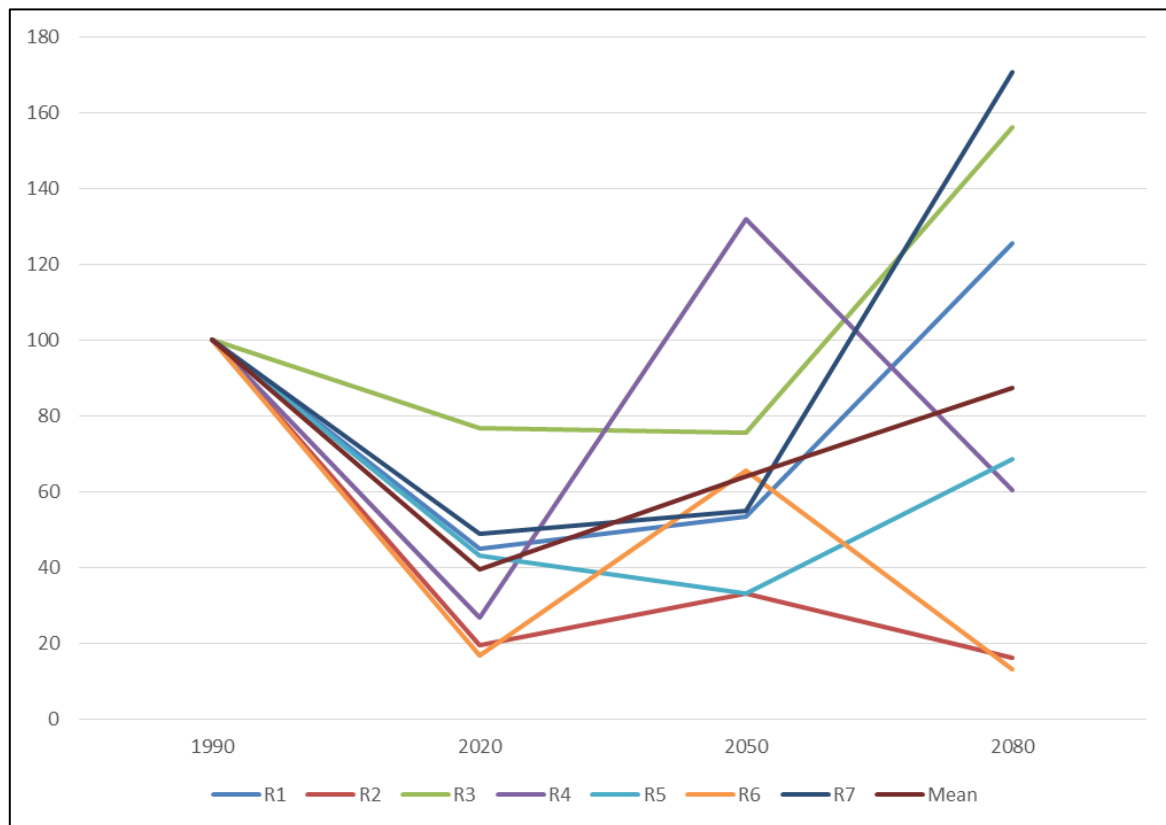
We compare the level of risk (expressed in terms of economic losses) between the baseline 100-year scenario and the upper and lower extremes of the 2080 projection. Specifically, we look at how the level of risk might change if the return period of the present-day 100-year scenario became 13 years or 170 years. For each case, we assume the same level of exposure and hazard intensity as presently. That is, we use the same flood hazard map, population density and electricity transmission system layout as today. Because the economic losses remain constant, the level of risk changes because of the change in probability. In addition, we compare the 13-year and the 170-year 2080 scenarios with the present-day scenarios with similar recurrence intervals, for which flood hazard maps are available. Specifically, we compare the 2080 13-year scenario with the present-day 10-year flood and the 2080 170-year scenario with the 200-year flood. Our analysis is not limited to the comparison of risk levels, expressed in terms of the expected economic losses. We obtain more information on the impact of floods on critical electric infrastructure by comparing the severity of each scenario, as well as the contribution of each type of cost to the total economic damage.

Table 2. Recurrence interval of the 100-year flood scenario for Hazardville based on the EURO-CORDEX climate scenarios

| EURO-CORDEX climate scenarios			Recurrence interval (in years) of the baseline 100-year flood		
	GCM	RCM	2020	2050	2080
R1	EC-EARTH	RACMO22E	44.8412	53.5447	125.477
R2	HadGEM2-ES	RCA4	19.3497	33.2637	16.2767
R3	EC-EARTH	RCA4	76.7393	75.7214	156.361
R4	MPI-ESM-LR	REMO2009	26.7913	131.867	60.3699
R5	MPI-ESM-LR	CCLM4-8-17	42.9839	33.0349	68.5358
R6	MPI-ESM-LR	RCA4	16.7636	65.6078	13.0743
R7	EC-EARTH	CCLM4-8-17	48.8822	54.8621	170.658
Ensemble Mean			39.47874	63.98594	87.25039
Standard Deviation			20.81643	33.7695	64.29947

4.3 Impacts

4.3.1 Data and assumptions

The Global Human Settlement Layer (GHSL) dataset (JRC & CIESIN, 2017) was used to derive population density spatial information. This dataset was developed by the JRC using multi-temporal collections of Landsat imagery. Landsat is the longest-running non-military Earth-observation program. The collection includes grids of built-up presence and population density for 1975, 1990, 2000 and 2015, in resolutions of 250 m and 1 km. In this study, the population density layer for 2015 (resolution of 250 m) was used to determine the number of people affected by the flood and the power outage.

The transmission grid layers were obtained from the Open Data Platform of the case-study country's Transmission System Operator (TSO). RTE's Open Data Platform includes datasets covering a wide range of topics, including consumption, generation, electricity trade within Europe, regional electricity reports and others. In this study, we used the layers of substations (RTE, 2017a) and transmission lines (RTE (2017b). Figure 5 illustrates the transmission lines and substations located in and around the study area. Within the boundaries of Hazardville, there are 41 transmission substations (maximum voltages of 225 and 63 kV) and over 227 km of transmission lines (225 kV and 63 kV). However, there are no power plants in Hazardville or in its immediate vicinity.

Figure 5. Map of transmission assets in and around Hazardville (black lines: transmission lines; black dots: transmission substations)
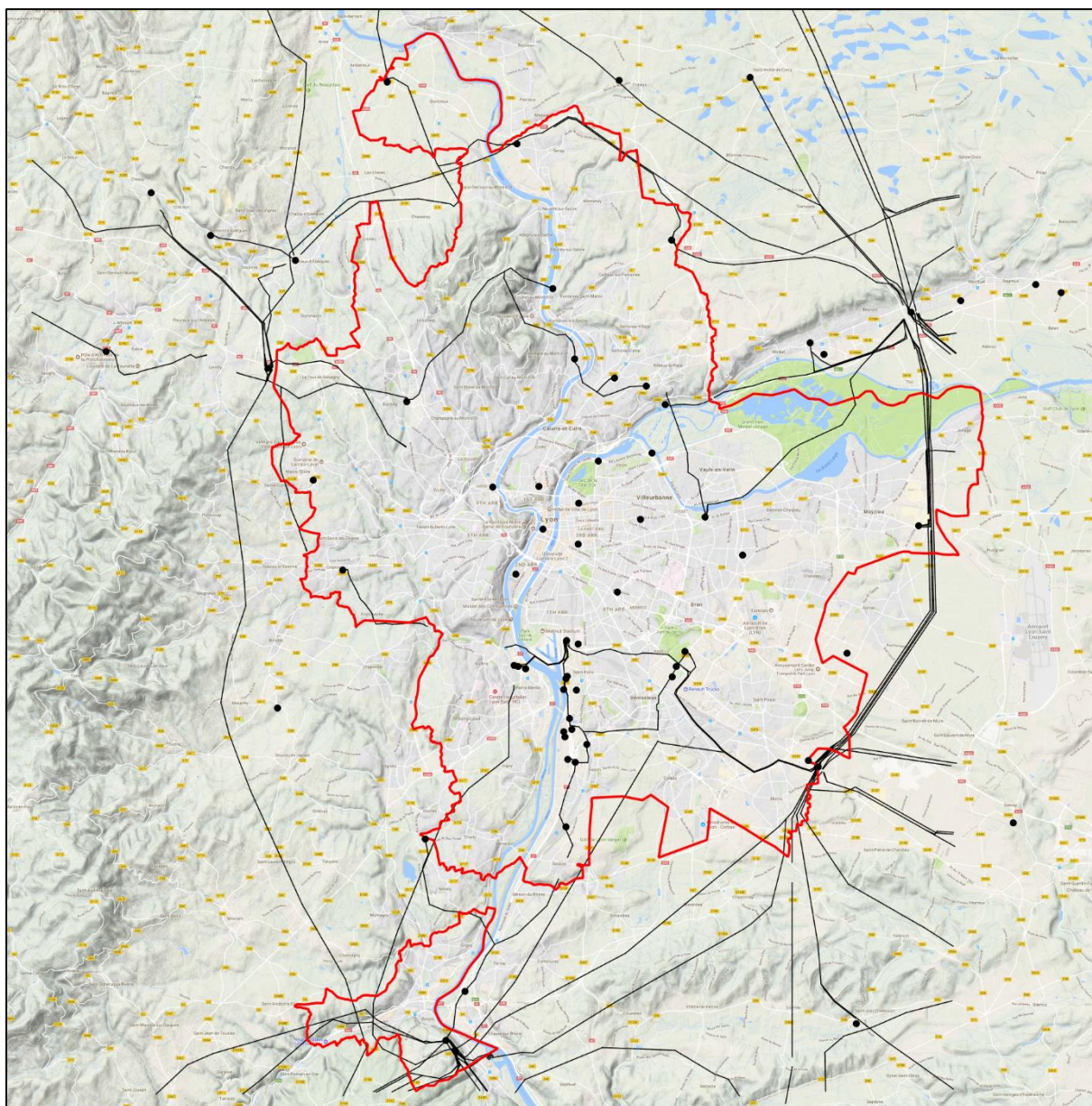

Source: JRC. Background: Google Maps®. Hazardville layers: https://www.data.gouv.fr/fr/ (accessed November 14, 2017). Transmission grid layers: RTE (2017a; b)

The damage functions for transmission grid assets (i.e. substations, transmission lines and power plants, Figure 6) were obtained from the flood model of HAZUS®-MH (FEMA, 2003; Scawthorn et al., 2006a; b). Damage functions are preferable to fragility functions for flood

risk analysis because, once a facility is inundated, water damages all the equipment and buildings inside. In other words, damage is 100% (FEMA, 2003). Here, depth-damage functions were used in conjunction with the flood hazard maps discussed in section 4.2.2 and the transmission grid layers to determine the level of flood damage to substations and transmission lines. The use of these particular functions relies on the assumption that the vulnerability of transmission grid assets in the study area are similar to the average values in the United States. It is also assumed that substation equipment is placed on the same height as in the United States. Specifically, the depth-damage functions included in HAZUS®-MH assume that electrical switch gear is located 3 ft (or approximately 0,91 m) above ground level (FEMA, 2003).

Figure 6. HAZUS®-MH depth-damage functions for transmission grid assets
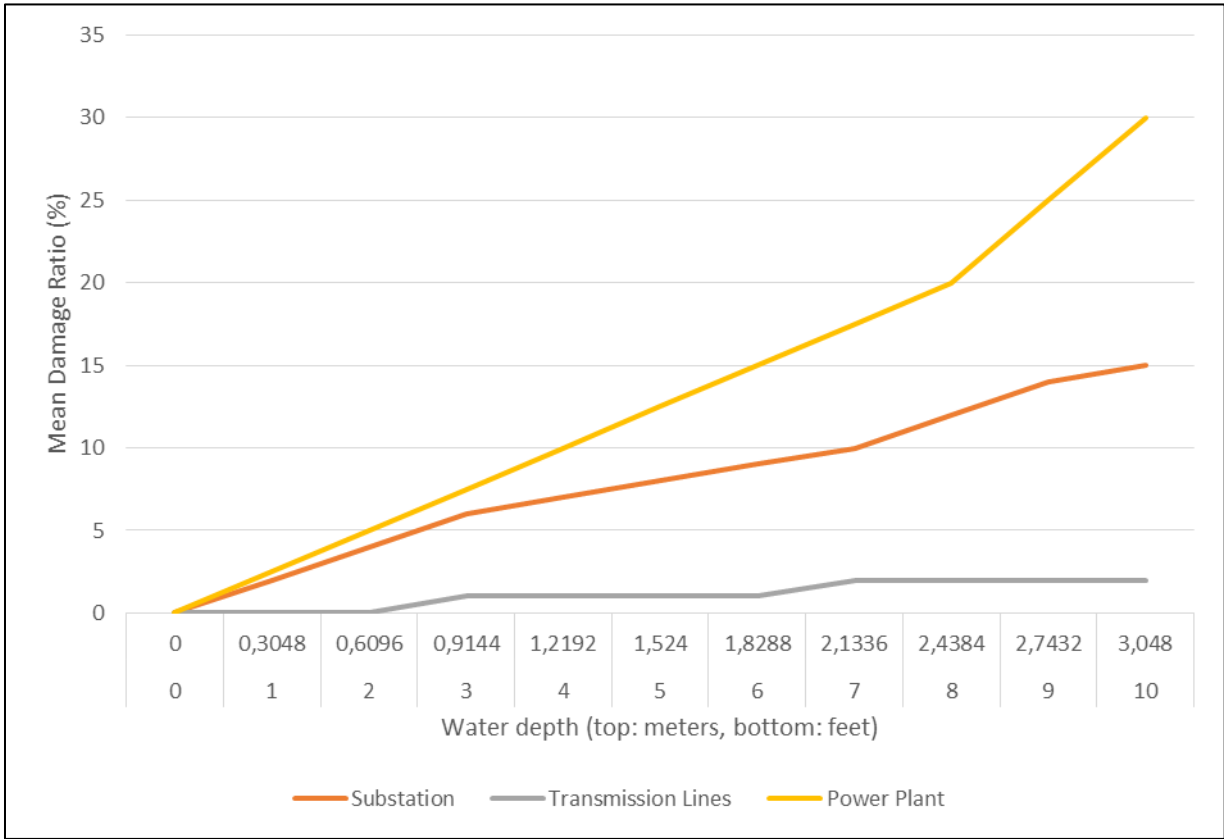
Source: Adapted from FEMA (2003)

One weakness of these damage functions is that they provide information for water depths of up to 10 ft (3,048 m) only. In this study, when the flood water depths exceeded this bound, two alternatives were compared. The first alternative was based on the assumption that the level of damage cannot exceed the maximum Mean Damage Ratio defined by the damage function, even when the water depth is greater than the upper bound of the function's domain. Therefore, when the estimated flood water depth exceeded 10 ft, the level of damage was assumed to be equal to the Mean Damage Ratio for 10 ft. In the second alternative, we extended the depth-damage function beyond the 10 ft bound. We used least squares estimates to fit polynomial and power functions to the depth-damage function, which yielded R^2 values exceeding 0,99. Because depth-damage functions represent statistical estimates, we compared the values of damage estimated derived with each approach to analyze the sensitivity of damage to this choice.

In addition, the damage functions for transmission lines utilized here were built based on the assumption that the vulnerability of transmission lines to inundation is low. Damage potential includes flooding of the ends of buried lines and the eventuality for barges hitting

transmission towers (FEMA, 2003). Yet, transmission towers are known to be vulnerable to landslides and soil erosion secondary to floods. The repair of isolated failures of transmission tower foundations due to soil erosion will be costly and time-consuming, because it will require the replacement of one or more downed transmission towers. Site access may be a problem, as floodwaters may block roads and make bridges impassable. However, these failures are unlikely to significantly delay the reconnection of electricity supply to customers, because workarounds are usually found, such as erecting temporary structures until replacement structures are built. On the other hand, landslides are likely to affect wider areas and therefore produce more widespread damage (Karagiannis et al., 2017). Therefore, the damage functions employed in this study probably underestimated the level of damage to transmission lines and the fraction of the total economic impact of the flood attributed to the repairs of transmission lines.

Furthermore, typical replacement values of transmission assets in the country in which Hazardville is located were identified through a review of the publicly available literature, including environmental impact assessments of recent projects. Table 3 outlines the replacement values for the categories of transmission grid assets located within the boundaries of Hazardville. These figures are intended to be representative for this case study, but should not be interpreted in any other context.

Table 3. Replacement value approximations for transmission grid assets

Asset type	Unit	Unit replacement value
225kV substation	EA	€ 9 million
63kV substation	EA	€ 3 million
Transmission line	km	€ 900,000

Source: Adapted from ERDF (2014a; b), and ICF Consulting (2002)

It was also assumed that none of the transmission grid assets (i.e. substations and transmission grid towers) are protected by dikes or levees. Therefore, all transmission grid assets are inundated to a water depth equal to the flood water depth indicated by the flood hazard map in that point. This is likely to lead to overestimation of the damage, because some substations may indeed be protected. In addition, substations are likely to be protected to some extent by surrounding structures, especially in European urban areas, where building density is relatively high and probably higher than in cities and towns in the United States.

4.3.2 Results

Table 4 illustrates the assumed duration of the flood episode and the power outage for the 10-year, 100-year and 200-year scenarios. These assumptions were approximated from empirical data discussed in Karagiannis et al. (2017). The evacuation of the affected population is assumed to begin at the same time as the power outage. While the affected area is under water, the flood episode and the power outage are ongoing concurrently. Once the flood waters recede, the flood episode ends and the outage continues for some time until the necessary repairs are conducted. These durations are meant as approximate average values of the time it takes for clients to have their electricity supply reconnected. The progressive recovery of electricity connections of individual clients is not simulated here, because average values were deemed adequate for the needs of this study.

Table 4. Assumed duration of the flood episode and power outage

Scenario	Flood duration (t_f)	Outage duration (t_{out})
10-year flood	3 days	5 days
100-year flood	6 days	10 days
200-year flood	7 days	11 days

The economic losses from the flood and outage combined for each flood scenario are indicated in Figure 7. In this case, the mean damage ratio was not allowed to exceed the value for 10 ft. The estimated total cost would exceed € 300,000,000 for the 10-year flood and € 800,000,000 for the 100-year flood and would be near € 900,000,000 for the 200-year flood. The total economic impact more than doubles between the 10-year and 100-year scenarios, and increases by approximately 10% between the 100-year and 200-year scenarios. We note from Table 5 that the losses from the disruption of the local economic activity are by far the major contributor to the economic impact of the flood and outage in all three scenarios, consistently amounting to about 99% of the total cost. Repairs to substations and transmission lines would each amount to less than 1% of the total cost in all scenarios. Thus, the increase to the total cost is driven by a proportionate increase of the losses from the disruption of the economic activity and of the cost of repairs to substations and transmission lines. In other words, the share of transmission asset repairs and business losses does not change substantially across the scenarios examined here. Of particular interest is the observation that the cost percentages remain virtually unchanged between the 100-year and 200-year scenarios.

Figure 7. Total cost of the flood and outage (damage functions bounded at 10 ft (3.048m))
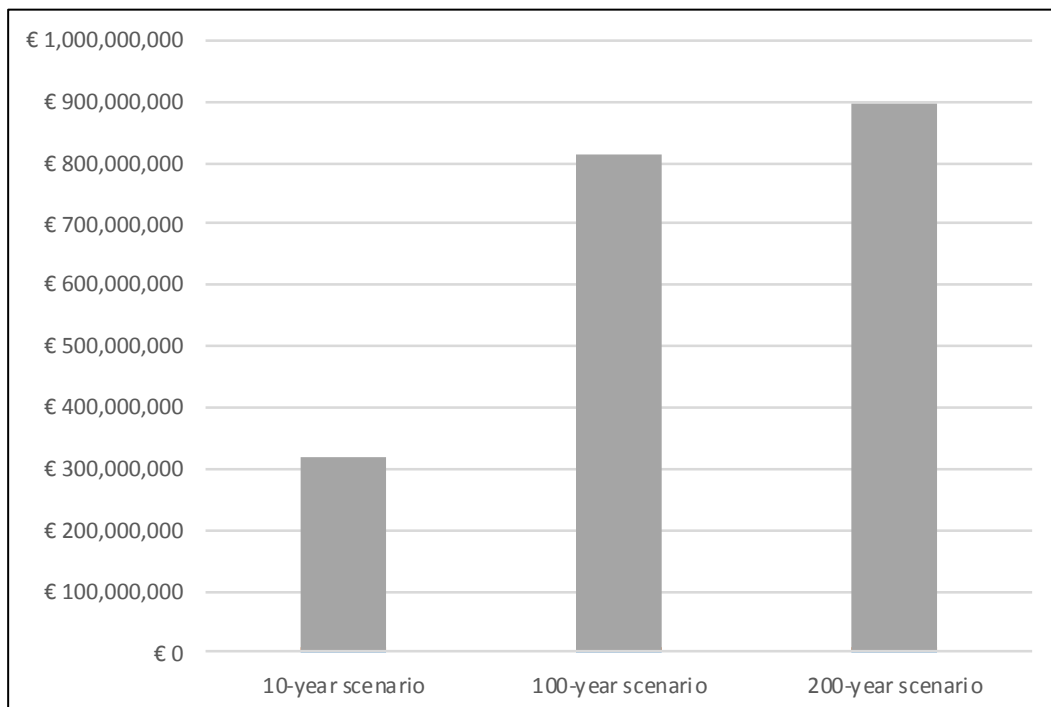
Table 5. Share of repairs and business losses to the total economic cost (damage functions bounded at 10 ft (3.048m))

Cost items	Distribution of the total economic cost		
	10-year flood	100-year flood	200-year flood
Substation repairs	0.60%	0.52%	0.52%
Transmission line repairs	0.06%	0.04%	0.04%
Disruption of the local economic activity	99.34%	99.45%	99.45%

Figure 8 shows the estimated losses from the flood and outage, if the damage functions were not bounded at 10 ft. The estimated total cost follows a similar trend as in the previous case. The total losses more than double between the 10-year and 100-year scenarios, and increases by approximately 10% between the 100-year and 200-year scenarios. From Table 6 we can see that the losses from the disruption of the local economic activity (business losses) represent again the lion's share of the impact of the flood and outage in all three scenarios and amount consistently to about 99% of the total cost. The costs of repairs to substations transmission lines would each amount to no more than 1% of the total cost. The increase to the total cost is driven by a proportionate increase of the losses from the disruption of the economic activity and of the cost of repairs to substations and transmission lines. The share of transmission asset repairs and business losses does not change substantially across the scenarios examined here as well.

Figure 8. Total cost of the flood and outage (unbounded damage functions)
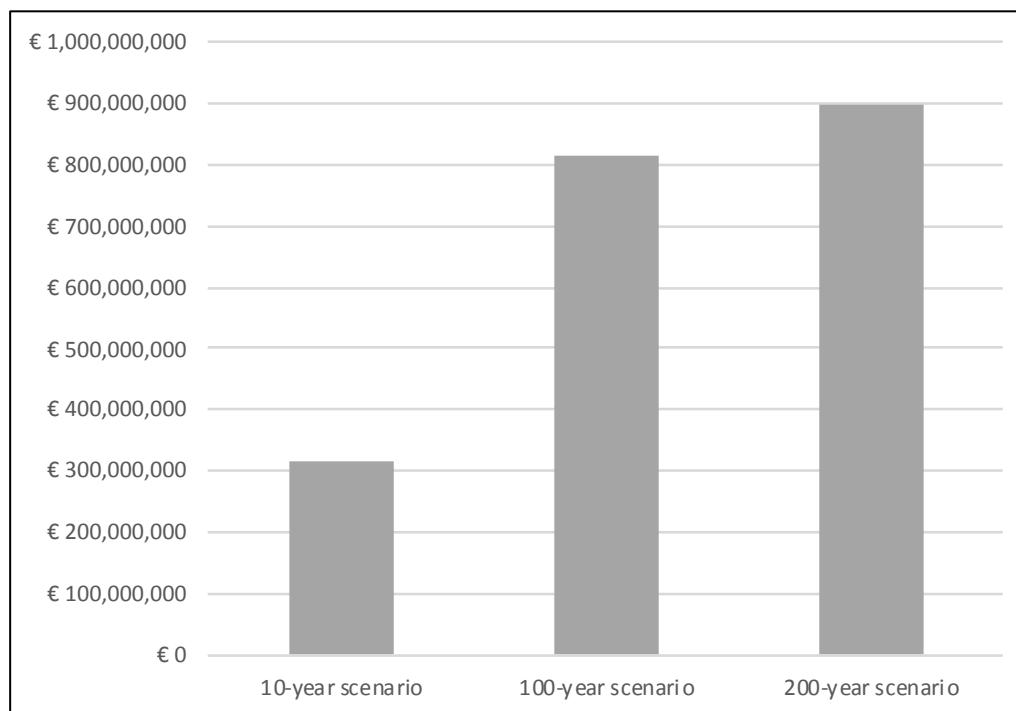
Table 6. Share of repairs and business losses to the total economic cost (unbounded damage functions)

Cost items	Distribution of the total economic cost		
	10-year flood	100-year flood	200-year flood
Substation repairs	0.64%	0.59%	0.60%
Transmission line repairs	0.09%	0.06%	0.05%
Disruption of the local economic activity	99.27%	99.36%	99.34%

The total economic losses are increased by a marginal 1% or less between the bounded and unbounded damage functions, hence the similarity on Figures 7 and 8. This is somewhat to be expected, considering that the total economic losses are driven by the cost of the disruption of local economic activity. On the other hand, the repair cost for substations and transmission towers is affected by the damage function used in the calculations.

The repair cost is proportional to the Mean Damage Ratio (MDR), which is determined from the damage function. Therefore, for the same water depth, unbounded damage functions produce greater MDR values and hence greater repair costs. Table 7 illustrates the relative increase of the cost of repairs of transmission assets between bounded and unbounded damage functions for each of the three scenarios analyzed in this study. The effect of extrapolating MDR values beyond the range of damage functions was more pronounced for substations than transmission lines. The use of unbounded damage functions increased the repair cost for substations by less than 17%, while the cost for transmission lines increased by approximately 47% to more than 50%.

Table 7. Relative increase of repair costs between bounded and unbounded damage functions

	10-year scenario	100-year scenario	200-year scenario
Substations	6.9%	13.7%	16.3%
Transmission lines	53%	47.9%	46.9%

Indeed, the flood water depth exceeded 3 m in some areas. One substation was exposed to water deeper than 5m and several transmission lines were under more than 6m of water in the 100-year and 200-year scenarios. Considering that the maximum flood depth was greater than the upper bound of the substation damage function range by 2/3, and more than double the upper bound of the range of the damage function for transmission lines, the increase of 11% to 17.5% is reasonable. However, this fluctuation indicates that the approximation of economic losses is sensitive to the bounds of damage functions.

However, the costs for substations and transmission lines follow opposite trends. The repair cost of substations increases more as the inundated area becomes larger. That is, the increase of the cost to repair substations in the 200-year scenario is greater than for the 100-year scenario, which is greater than for the 10-year scenario. On the other hand, the repair cost of transmission lines does increase with the use of unbounded damage functions, but the effect is less pronounced as the inundated area increases in size. That is, the increase of the cost to repair transmission lines in the 200-year scenario is less than

for the 100-year scenario, which is less than for the 10-year scenario. In summary, extrapolating MDR values beyond the range of damage functions increases the estimated repair cost for both substations and transmission lines. Yet, as the inundation area becomes larger, the effect increases for substations and decreases for transmission lines.

Because they are calculated deterministically, the business losses are not affected by the use of unbounded damage functions. The estimated losses from the interruption of the daily economic activity rise sharply when the areas affected by the flood and the power outage are considered in the analysis. Figure 9 compares the estimated losses calculated from the interruption of economic activity for the inundated area alone versus that in the area affected by the power outage as well. The business losses incurred by the combination of the flood and the power outage are between 6 and 8 times those generated by the flood alone. Each substation is assumed to provide power to the area around it which is closer than any other substation. Therefore, when a substation is shut down, all users in that area experience a blackout. The result is that the area affected by the power outage is considerably larger than the inundated zone.

Figure 9. Estimated economic losses from the disruption of daily economic activity from the flood alone (orange) and the combined impact of the flood and power outage (blue)
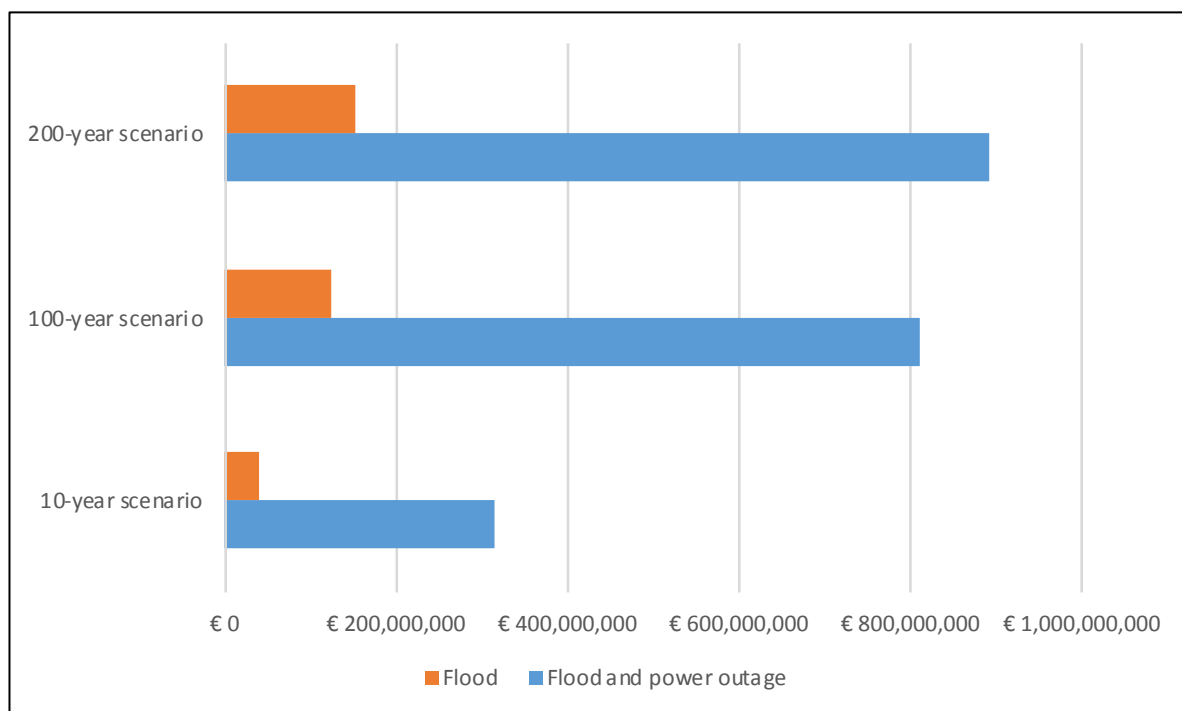
For instance, Figure 10 illustrates the areas that would be affected by the outage versus the flood zone for the 100-year flood scenario in our example. Under the assumptions discussed in sections 3.2.2 and 3.2.3, the larger the area affected by the flood or the outage, the more of the local economic activity is interrupted, and the more people would not go to work. In addition, the outage would last longer than the flood, because of the time needed to conduct repairs to the affected transmission assets. Therefore, the interruption of local business operations would last longer in the area affected by the outage.

23

Figure 10. Areas affected under the 100-year flood. Left: inundated area (black and white color gradient indicates water depth). Right: area affected by power outage (grey shade).
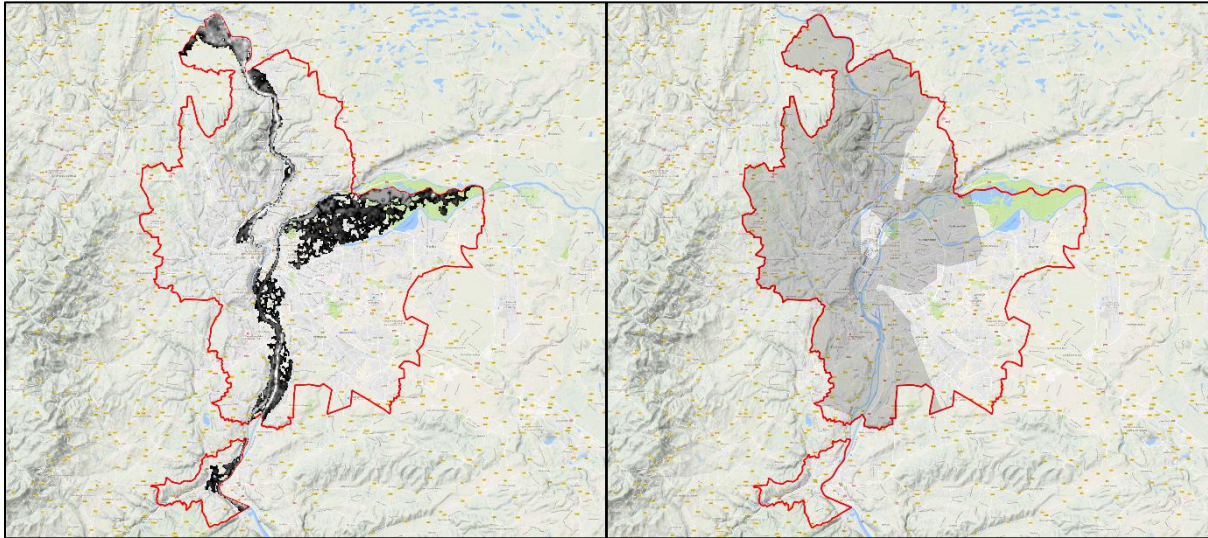

Source: JRC. Background: Google Maps®. Hazardville layers: https://www.data.gouv.fr/fr/ (accessed November 14, 2017). Flood hazard map layers: JRC & CIESIN (2015)

Furthermore, the size of the flood zone increases as the scenario probability decreases. Lower probability scenarios would also result in longer flood episodes and would hence result in longer interruption of the areas affected by the flood or the ensuing power outage. The increase is more pronounced between the 10-year and 100-year scenario than between the 100-year and 200-year scenario. When only the flood-affected area is considered, the business losses more than double between the 10-year and 100-year scenario, but increase by only about 22% between the 100-year and the 200-year scenario. When both the flood and outage are considered, then the estimated cost from the interruption of daily economic activity for the 200-year scenario is about 10% greater than the 100-year scenario, but the estimated losses for the 100-year scenario are more than one and a half times those of the 10-year scenario. In this case, this sizeable rise can be traced back to the increase of the area affected by the power outage. It is estimated that a 100-year flood would cause the preemptive shut down of 6 more substations than the 10-year flood. Moreover, the duration of the inundation and the resulting electricity outage was estimated to be longer for the 100-year flood than for the 10-year flood. In other words, the 100-year scenario would affect a larger area for more time, hence the sharp rise of the estimated economic losses. On the other hand, the same substations would be preemptively shut down before the 100-year and the 200-year flood. Therefore, the small relative increase of the estimated losses is due only to the slightly longer duration of the inundation and the power outage.

4.4 Change in the level of risk

This section discusses the change in the level of risk posed by the 100-year scenario. The level of risk is estimated based on the expected economic losses from the flood and the power outage it triggers. Figure 11 is a risk chart which illustrates the scenarios analyzed in this study (the bounded damage functions were used to determine the risk level). Risk charts are used to map risks based on their likelihood of occurrence and their consequences. Each scenario is plotted on the chart based on its annual probability of occurrence (vertical axis) and its estimated severity, in terms of the estimated total economic losses (horizontal axis). The position of each scenario determines its level of risk and therefore its priority. High-probability and high-severity scenarios are located at the top right corner of the chart, and warrant the highest priority in risk reduction strategies. Here, the black dots represent the baseline 10-year, 100-year and 200-year scenarios.

Figure 11. Change in the level of flood risk to critical electric infrastructure
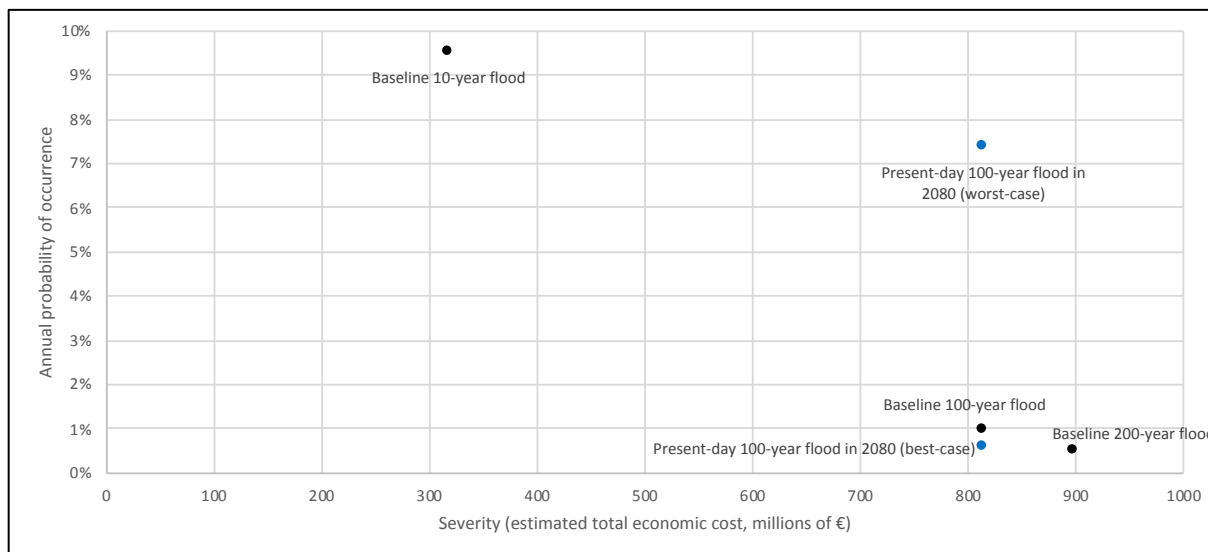
The probability of occurrence is calculated from the return period, assuming a Poisson process. The results of our analysis indicate that, in the coming decades, climate change will likely change the probability of the present-day (baseline) 100-year flood in the study area. The calculations described in section 3.1 were conducted using the methodology outlined in Alfieri et al. (2015a). Seven climate change models were used to estimate how the return period of the present-day 100-year flood might change by 2080. The results indicate that the return period of the present-day 100-year flood could range from approximately 13 years (worst-case) to 170 years (best-case) in 2080. These two extremes are represented by the blue dots in Figure 10. The severity of these two scenarios is the same as that of the present-day 100-yer scenario, because the same flood hazard map is used for the analysis. Therefore, on the risk chart, the blue dots are located on a vertical line which passes from the baseline 100-year flood (black dot).

Table 8 illustrates the calculations of the level of risk. Among the baseline scenarios, the 10-year scenario comes with a highest level of risk, which is the product of the occurrence probability and the economic losses, and the 200-year scenario is associated with the lowest level of risk. Since the losses are of the same order of magnitude for all scenarios, the risk level is dominated by the scenario occurrence probability. The level of risk of the 100-year flood is 80% greater than that of the 200-year scenario, and the risk from the 10-year flood is more than three times that of the 100-year flood. The difference between the 2080 best case and the worst-case scenarios is substantial.

The best-case "climate-change" scenario has a return period of 170 years. Among the baseline scenarios for which flood hazard maps exist, the 200-year flood has the closest probability of occurrence to the best-case "climate-change" scenario. In the absence of flood hazard maps for a present-day 170-year flood, a comparison between the present-day 200-year scenario and the best-case "climate-change" scenario could give an indication of the change in the level of risk. The 2080 recurrence interval of the best-case scenario is approximately 170 years, i.e. within 30 years of the baseline 200-year flood. The severity of the 200-year flood is only 13% greater than that of the best-case 2080 scenario (which is the same as the severity of the baseline 100-year scenario). In this case, the expected losses are slightly higher for the climate-change scenario.

Table 8. Risk as expected losses

Scenario	Return period (years)	Annual probability of occurrence (event/year)	Losses (€)	Expected losses (€)
Baseline 10-year flood	10	9.516258E-02	317,758,351.51	30,238,705.17
Present-day 100-year flood in 2080 (worst-case)	13	7.363405E-02	814,192,952.36	59,952,326.37
Baseline 100-year flood	100	9.950166E-03	814,192,952.36	8,101,355.24
Present-day 100-year flood in 2080 (best-case)	170	5.842538E-03	814,192,952.36	4,756,953.40
Baseline 200-year flood	200	4.987521E-03	898,052,014.06	4,479,053.11

Similarly, the worst-case "climate-change" scenario has a return period of 13 years. Among the baseline scenarios for which there exist flood hazard maps, the 10-year flood has the closest probability of occurrence to the worst-case "climate-change" scenario. In the absence of flood hazard maps for a present-day 13-year flood, a comparison between the present-day 10-year scenario and the best-case "climate-change" scenario could give an indication of the change in the level of risk. The 2080 recurrence interval of the worst-case scenario is approximately 13 years, i.e. within 3 years of the baseline 10-year flood. However, the severity of the worst-case 2080 scenario is more than twice that of the present-day 10-year flood. Therefore, the expected losses for the climate change scenario are nearly double those of the present-day scenario.

5   Discussion

The purpose of this study was to present a methodology for understanding the change in the economic risk level posed by floods to critical infrastructure and to show the application of the methodology by means of a case study. We have focused on critical electric infrastructure as a first step. In what follows, we first discuss the implications of this study for disaster risk assessment and risk reduction strategies. Subsequently, we outline the limitations of the case study and implications for future research. We conclude with a consideration of the potential for extending the methodology to other types of hazard and/or different categories of critical infrastructure.

5.1   Risk assessment and risk reduction

This section discusses the implications of this study for disaster risk assessment and risk reduction strategies. One of the key objectives of any risk analysis is to inform decision-making regarding risk reduction measures. However, it is important to point out that this study is neither intended to replace nor question official risk assessment exercises or any resulting risk reduction measures. Rather, we attempt to inductively reach more generalized conclusions pertaining to the nature of disaster risk assessments and strategies aiming at building resilience into the power grid.

More people are affected by the outage caused by the flood than by the flood itself. As discussed in section 4.3.2, the impact of the flood on the business cost is between 6 and 8 times lower than that caused by the combined effects of the flood and ensuing power outage. In addition, the cost emanating from the disruption of the daily economic activity accounts for the greatest part (99% or more in all scenarios). On the other hand, the cost of repairs to electricity infrastructure assets does not exceed 1% of the total damage. These results have implications for disaster risk assessments and for the resilience of critical electric infrastructure.

Flood risk analyses should base their estimates not only on the cost of repairs to inundated power grid assets, but also on the economic damage resulting from the interruption of daily economic activity. This study shows that not including the business cost to the estimation of the losses from a flood scenario would likely underestimate the severity by up to 100 times. Furthermore, when the potential for a preemptive shutdown of exposed substations is taken into consideration, the estimation of the number of exposed people increases substantially, which changes the risk scenario altogether. Besides the argument in favor of expanding the loss estimation conducted during disaster risk assessment exercises to include detailed estimates of power grid damage, the results of this study demonstrate the vulnerability of modern economies to critical electric infrastructure outage. In this sense, this study justifies the inclusion of long-term power outages as separate scenarios in a number of National Risk Assessments, as discussed in chapter 2.

In addition to the implications about the methodology of disaster risk assessments, the results of this study highlight the need to reduce the risk posed from floods to critical electric infrastructure, especially in light of the potential increase of the frequency and severity of floods brought on by climate change. Among the baseline scenarios, the highest level of risk (expressed in terms of economic losses) is posed by the most likely floods. Despite resulting in a larger inundation zone and greater economic costs, the least likely flood scenarios were associated with a relatively low risk level in this study due to a lower occurrence probability. Conversely, the repeated damage caused by the 10-year flood, albeit minor compared to the 100-year and 200-year scenarios, would result in greater expected losses, because of the higher probability of occurrence.

Reducing the level of the risk posed to critical electric infrastructure from floods would entail implementing solutions aimed at reducing the probability of a flood occurring, at reducing the impact of the flood on critical power grid assets, or a combination of the above. Approaches based on urban planning (such as changing land use near the river), structural protection (such as building levees), or a combination of both (such as increasing the size of the flood fringe) would all be justified in principle, but remain beyond the scope

of this study. From this study's perspective, such measures should be undertaken only to the extent that they are supported by exhaustive analyses of the level of risk posed from the flood, not only to critical electric infrastructure, but to the entire community. The long-term cost of risk reduction measures aimed at reducing the probability of the flood should be gauged against the expected losses to all critical infrastructure sectors in Hazardville. In addition, any modification of the floodplain of the two rivers converging in Hazardville should also consider the potential effects on communities upstream and downstream of the city.

Considering that expected losses result mainly from the business cost, risk reduction efforts should be resilience-driven and aimed at the whole community. One example would be to encourage business owners to design and implement an emergency management program, including developing and maintaining business continuity plans, purchasing insurance and taking measures to protect their business from water damage.

From the perspective of TSOs and DSOs, courses of action aimed at reducing the impact of floods on the power grid would likely prioritize assets based on the proportion of the total damage that results from their inundation during a flood scenario. In this study, substation damage amounted to about 10 times the damage on transmission line assets. Therefore, protecting substations is likely to substantially decrease the economic damage of the flood. Flood damage occurs when a substation is inundated and, once it is inundated, water affects all the equipment and buildings inside. Therefore, substation protective measures should be designed to prevent the substation from being inundated, or making sure the water does not reach the level of critical equipment. In addition, protecting substations from being inundated may eliminate the need for a preemptive shut down, thus reducing the number of people experiencing a blackout.

From a technical point of view, the most popular options for protecting substations from floods are relocating the most exposed substations outside the affected area, erecting levees and elevating sensitive equipment above the expected flood water depth (Karagiannis et al., 2017). Relocating substations is technically complex and will likely be the most expensive alternative. The cost of relocating a transmission substation includes the acquisition of new land, construction, equipment investments, changing the physical configuration of the grid around the substation (e.g. erecting new transmission towers), as well as dismantling the old facility. In addition, relocating too many substations may reduce the reliability of the power grid, which is crucial to the economic activity of urban areas. However, it may be the only solution in some cases and it effectively eliminates the risk. For example, a substation in Queensland, Australia suffered no damage from the 2010 floods because it was located well above the 100-year flood level (Karagiannis et al., 2010).

Building levees around a substation and/or elevating critical equipment above the expected flood water depth may be more cost-effective solutions. Another substation in Queensland, Australia was inundated during the 2010 floods, but the water did not reach the height of critical equipment, and the area surrounding the substation experienced a blackout of no more than 3 hours (Karagiannis et al., 2017). However, both approaches need to consider the expected water depth, which increases with the recurrence interval of the flood scenario. Planning for too shallow an inundation will only instill a false sense of security. Substation levees should be sufficiently high and equipment should be elevated beyond the reference flood. This naturally begs the question about the choice of the reference flood.

For this particular case study region, if climate change is not considered, the highest risk, in terms of the expected economic losses to power grid assets, is caused by the 10-year scenario. In addition, substation damage is responsible for the greatest part of the expected losses. Therefore, measures to protect the substations exposed to this flood would likely be the most economically viable. On the other hand, if climate change were considered, it is the worst-case 2080 scenario which yields the highest expected losses. Therefore, protection measures should be targeted at the substations exposed to this scenario, and the reference flood should be aligned with that water depth. The 2080 worst-case scenario is none other than the present-day 100-year scenario, only with a different

return period. In other words, the same power grid assets are inundated in the 2080 worst-case scenario as in the present-day 100-year flood. In addition, the water-depth of the 2080 worst-case scenario is the same as the present-day 100-year flood for each substation. Therefore, if climate change was considered, the reference flood for designing protection measures should be the present-day 100-year flood.

5.2 Limitations

The scope of this study was to demonstrate a methodology for the estimation of the risk posed by floods to critical infrastructure, given the change in flood frequency and severity driven by climate change. The limitation in scope was deemed necessary to maintain the level of specificity to critical infrastructure and climate change, but it came with several limitations, which are outlined below.

First and foremost, the results of this study are critically dependent on the potential uncertainties in the data and the climate models used. Ensemble projections indicate that the flood hazard may increase in the study area, yet there is considerable climate uncertainty around these central estimates. Even when mean values are considered, the return period of the present-day 100-year flood could be as low as 13 years or as high as 170 years by 2080. In addition, the assumptions about population density in the study area, and the duration of the flood and the power outage all severely affect the results of this study. For example, an increase of the population density by 10% or a single-day increase in the assumed duration of the flood episode and resulting power outage would each cause the estimated business loss to rise by approximately the same percentage in the baseline 100-year scenario.

Second, the depth-damage functions used in this study were, in some cases, incomplete, adding another layer of epistemic uncertainty to our estimations. One issue was that the damage functions describing the impact of the flood on substations were bounded at 10 ft (3,048 m). Because the estimated flood depths exceeded that limit on several cases, a sensitivity analysis was conducted to address the impasse. Two alternatives were considered: one where the damage functions were bounded at 10 ft even when the water depth exceeded that value, and another where the damage estimations were extrapolated beyond the range of the depth-damage function. Another problem was that depth-damage functions for transmission lines only accounted for flooding of the ends of buried lines and the eventuality for barges hitting transmission towers (FEMA, 2003). However, transmission towers may be vulnerable to landslides and soil erosion secondary to floods (Karagiannis et al., 2017). In one study we reviewed (Aguet & Ianoz, 2001), transmission towers may account for up to 50% of the cost of transmission lines. Hence, not accounting for the vulnerability of transmission lines may result in a gross underestimation of the total economic damage and of the proportion of the transmission tower repair cost to the total cost.

Third, this methodology does not consider the interdependencies between the power grid and other critical infrastructure. The vulnerability of critical infrastructure to a wide range of hazards and threats is notoriously shaped by interdependencies which result in failures cascading across many different critical infrastructure categories (Rinaldi et al., 2001; Pescaroli & Alexander, 2016). In addition, electricity is recognized as the single critical infrastructure sector upon which all other depend, to a greater or lesser extent. For instance, Karagiannis et al. (2017) have demonstrated that power outages resulting from natural disasters, including floods, have disrupted telecommunications and compromised the capabilities of emergency services. Not considering the impact of the power outage on other critical infrastructure sectors likely resulted in an underestimation of the severity. For example, if the estimation included the income losses incurred by the telecommunications sector because of the temporary shutdown of some cell arrays due to the power outage, then the total cost would arguably have been higher.

Fourth, this approach does not consider the redundancies built in the transmission grid. Electric transmission and distribution grids are known for their high reliability, which is at

least partially achieved by building redundancies in the network topology. In other words, electricity networks are designed so that, if any one circuit fails for whatever reason, power may be rerouted through other circuits with minimal loss of time and energy (Short, 2004; Kersting, 2002). Conversely, this study has assumed that, if a substation is shut down, either because of contact of sensitive equipment with water or preemptively, then the area being served by this substation will automatically experience a blackout. This assumption is to a certain extent supported by empirical data (Karagiannis et al., 2017), but it may be only partially true. If a part of an area served by a substation can receive power through another substation as well, then that part may not experience a blackout if the first substation is shut down. Therefore, the assumption that the area surrounding a substation experiences a power outage when the substation is affected by the flood may result in an overestimation of the damage due to the interruption of daily economic activity. However, the proportion of the latter to the total economic cost of the outage is small, therefore the effect will be limited.

Last, the case study area is a large urban center with considerable economic activity. In addition, urban areas have far greater population densities than suburban or agricultural areas. Therefore, the economic impact of the flood or the outage on the local economy is likely to be exaggerated. For instance, in the estimation of the Business Cost (cf. section 3.2.2), a higher population density will yield a greater number of people inside the influence area of either the flood or outage for a large urban center like Hazardville compared with an agricultural area (irrespective of whether the influence area is estimated using Thiessen polygons or through arguably more accurate data provided by local authorities or a DSO). The size of the local economic activity (expressed in terms of GDP/capita/day) will also be higher for Hazardville. In addition, one may argue that a large urban center like Hazardville will likely have a higher concentration of transmission assets, including substations and transmission lines. Therefore, the exposure of these assets to inundation will be greater than in a suburban or an agricultural area. Nevertheless, this argument is related to the increased vulnerability of urban areas to natural disasters (McClean, 2010), which is beyond the scope of this study.

5.3 Future outlook

Despite the inherent limitations of this study, the results of the analysis offer a valuable insight into the risk to critical infrastructure from floods. Moreover, this study demonstrated the use of the methodology discussed in chapter 3, as a first step towards the development of a more comprehensive approach. Here, we discuss the possibility for extending the methodology used in this study and then we briefly outline the potential for future work.

The methodology described in chapter 3 can be readily extended to other types of critical infrastructure, as long as depth-damage functions are available. As highlighted in section 5.2, the estimation of the damage will depend to a large extent on the type of depth-damage function selected. In addition, different assumptions about the disruption of daily economic activity will apply for different types of critical infrastructure. In this study, we assumed that the daily economic activity is interrupted in the area affected by a power outage. Whereas this may be a realistic assumption for electricity, it is not for most other types of critical infrastructure. For instance, the local economy would probably slow down, but not brought to a halt, if there were no more water or gas, or if government services would stop working. However, the disruption of other critical infrastructure, such as healthcare or emergency services, would probably have other types of consequences, such as increased morbidity and mortality from the flood, but this would have to be assessed on a local level based on residual capacity. In either case, the Total Cost (TC) would be estimated, similar to section 3.2.4, as the sum of the damage to critical infrastructure (Total Repair Cost – TRC) and of the impact to the local economy resulting from the flood and the disruption of all critical infrastructure sectors combined (Business Cost – BC):

$$Total\ Cost\ (TC) = TRC + BC$$

The Total Repair Cost would include the sum of the damage to each critical infrastructure sector (which would be estimated in a similar way as in section 3.2.1):

$$Total\ Repair\ Cost\ (TRC) = \sum_{k=1}^{l} \sum_{j=1}^{m} \sum_{i=1}^{n} f_{jk}(x_{ijk}) \cdot RV_{ijk}$$

where:

— $i = 1, 2, …, n$: facilities or assets belonging to each category

— $j = 1, 2, …, m$: categories of facilities or assets

— $k = 1, 2, …, l$: critical infrastructure sectors

— RV_{ijk}: replacement value of each facility or asset i (of each category j of each critical infrastructure sector k)

— x_{ijk}: water depth at each facility or asset i (of each category j of each critical infrastructure sector k)

— $f_j(x_{ij})$: depth-damage function of facility or asset category of each critical infrastructure sector

For the estimation of the Business Cost (BC), a similar approach as in section 3.2.2 would be followed, but the numerator should include additional terms to quantify the cost incurred from the slowing down or interruption of the daily economic activity due to the disruption of multiple critical infrastructure sectors. Another alternative could be the use of an appropriate economic model to account for the indirect social losses (Scawthorn et al., 2006b), but this would not allow to determine which part of the losses is due to the disruption of critical infrastructure. Despite its feasibility, however, this approach would not consider the interdependencies among critical infrastructure sectors.

In a similar fashion, this methodology can be readily extended to other natural hazards, provided appropriate statistical correlations exist between the intensity of a hazard and the level of damage to critical infrastructure facilities or assets. For instance, fragility functions (or curves) are used to quantify the cumulative distribution function of the capacity of diverse types of buildings, facilities and assets to earthquakes. In contrast to damage functions, fragility functions do not describe the Mean Damage Ratio, but the probability of failure under a defined load. The capacity is measured in terms of the Peak Ground Acceleration (PGA) for earthquakes (Pitilakis et al., 2014) or wind pressure load for hurricanes and storms (FEMA, 2003b). Multiple types of critical infrastructure may be assessed for each hazard, as discussed above. However, neither this approach would be able to take into account the interdependencies among critical infrastructure sectors.

Other opportunities for future research include improving the available depth-damage functions so that they can account for damage caused by flood depths greater than 10 ft. Another possibility for further development is the improvement of depth-damage functions to account for additional damage potential, such as the failure of transmission tower foundations due to soil erosion and/or landslides. Last, this study was based on damage functions developed in the United States, the alignment of which with European critical infrastructure assets has yet to be confirmed. Therefore, the development of depth-damage functions specific to Europe, or the assessment of the degree to which existing depth-damage functions are representative of the vulnerability of European critical infrastructure would go a long way in improving this and similar studies conducted in the future.

6 Conclusions

The purpose of this study has been to demonstrate a methodology to assess the impact of climate change on the risk posed by floods to critical infrastructure in Europe. A case study was conducted in a large urban center in Western Europe, focusing on the electricity critical infrastructure subsector and the potential for economic losses due to floods. We derived the projected probability of a present 100-year flood scenario in the case study area from the pan-European flood risk assessment under high-end climate scenarios conducted by the JRC. Flood hazard scenarios were analyzed using JRC's Flood Hazard Maps. It was assumed that the transmission substations in the inundation zone would be preemptively shut down to minimize the level of damage, thus causing a power outage in the areas receiving electricity from these substations. The analysis included the potential damage to critical electric infrastructure facilities and assets, and the losses resulting from the disruption of the daily economic activity in the area affected by the power outage.

Ensemble projections indicate that the flood hazard may increase in the study area, yet there is considerable climate uncertainty around these central estimates. Specifically, estimations based on 7 climate change scenarios project the recurrence interval of the present 100-year flood from approximately 13 years to 170 years by 2080.

We found that the economic losses due to the interruption of the daily economic activity are 6 to 8 times greater if the power outage is taken into consideration than if only the area affected by the flood is taken into account. In addition, the losses from the loss of daily economic activity far outweigh the cost of transmission asset repairs, and amount to 99% of the total cost. Of the remaining less than 1%, the cost of substation damage is 10 times greater than damage to transmission. The severity of the flood and power outage combined for the 100-year flood is more than double that of the 10-year scenario. The increase results mainly from the inundation of a considerably larger area in the 100-year scenario and from the assumption of a longer duration of the flood and power outage. In other words, the 100-year flood affects more businesses and for a longer time. On the other hand, the total economic cost increases by only about 10% between the 100-year and 200-year scenario. The increase is due to the combination of greater water depths at all power grid assets and a slightly wider area affected by the flood.

Despite having a low severity, flood scenarios with a low return period yielded the highest level of risk (expressed in terms of economic losses) in this case study. In other words, the repeated impact of high probability/low severity floods is likely to have more sinister consequences than low probability/high severity events. The outcomes of the assessment methodology used in this study indicate that substations located in the 10-year inundation zone should be given priority in protection works, while the latter should ideally be designed to withstand the 100-year flood. In addition, the outcomes of this study advocate in favor of a resilience-oriented strategy, involving the whole community. For example, encouraging business owners to design and implement an emergency management program would go a long way towards helping the community build resilience.

The methodology can be readily extended to other critical infrastructure sectors, provided the availability of depth-damage functions. It may also be extended to other hazards, as long as there exist statistical correlations between the intensity of the hazard and the level of damage. For example, fragility functions are available for earthquakes and hurricanes. In either case, however, it is impossible to account for the interdependencies among critical infrastructure sectors. Possibilities for future research include the improvement of depth-damage functions. These should also be validated for European infrastructure systems, or new ones should be developed.

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List of abbreviations and definitions

CBRNE   Chemical, Biological, Radiological, Nuclear, Explosive

DSO   Distribution System Operator

EFAS   European Flood Awareness System

GDP   Gross Domestic Product

GHSL   Global Human Settlement Layer

GloFAS Global Flood Awareness System

NRA   National Risk Assessment

PGA   Peak Ground Acceleration

RTE   Réseau de Transport d'Electricité

TSO   Transmission System Operator

WMD   Weapons of Mass Destruction

List of figures

List of tables

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