This Project has received funding from European Comission by means of Horizon 2020, The EU Framework Programme for Research and Innovation, under Grant Agreement no. 700174

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RESILIENCE TO COPE WITH CLIMATE CHANGE IN URBAN AREAS.

Deliverable 3.1: Selection of methods for quantification of impacts of identified hazards

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Date: 01 March 2017

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RESCCUE - RESilience to cope with Climate Change in Urban arEas - a multisectorial approach focusing on water
Grant Agreement no.700174.

DELIVERABLE NUMBER:	3.1
DELIVERABLE NAME:	Selection of methods for quantification of impacts of identified hazards
WP:	WP3
DELIVERY DUE DATE:	31/10/2016
ACTUAL DATE OF SUBMISSION:	01/03/2017
DISSEMINATION LEVEL:	
LEAD BENEFICIARY:	UNEXE
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Document history

DATE	VERSION	AUTHOR	COMMENTS
04/11/2016	1	B. Evans	First draft for review by partners involved in 3.1
10/11/2016	2	B. Evans	Re-wording of section 3.9.1, Figure 7 revised to highlight Depth Damage Curve usage
24/11/2016	3	B. Evans	Incorporating changes suggested by Maria Almeida
28/11/2016	4	B. Evans	Incorporating information from Jaume Amorós and Beniamino Russo

02/12/2016	5	B. Evans	Reformatting document
09/12/2016	6	B. Evans	Minor additions based on feedback from Beniamino Russo
20/12/2016	7	B. Evans	Layout changes and additions
28/12/2016	8	M. Velasco	General review of the document
03/01/2017	9	B. Russo	New version of the document with several additions
13/02/2017	10	B. Evans	Amendments made based on feedback
15/02/2017	11	M. Velasco	References updated
21/02/2017	12	B. Evans	References updated
01/03/2017	13	B. Evans	Minor additions made based on external reviewers feedback

1. **Changes with respect to the DoA**
   None

2. **Dissemination and uptake**
   Public (PU). The report is fully open and will be distributed through the web

3. **Short Summary of results (<250 words)**
   Deliverable 3.1 – "Selection of methods for quantification of impacts of identified hazards" provides a review of methods/approaches used in a variety of sectors including Water, Energy, Waste and Transport to quantify impacts from climate driven events. Using outputs of identified hazards taken from deliverable 2.1 as an initial framework, this review provides a basis of understanding of the *state of the art* research in these fields that can be both utilized and potentially be built upon.

4. **Evidence of accomplishment**
   This report provides a good basis and summary of methods currently employed in the quantification of impacts on the major/critical services and infrastructures that are vital components in the smooth running of a city. By defining these and understanding their vulnerabilities a proactive/mitigation approach can be employed to improve the city's overall resilience.

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Abstract

Numerous studies over the years have looked into the effects of climate driven events on population, infrastructures and services within cities; and in more recent times there has been an increase in trends to look at the indirect effects of impacts resulting in failures of services and infrastructures due to the failure of a donor service or infrastructure upstream within a chain of linked systems. This review document looks at the different services that are being investigated as part of the RESCCUE project and the latest research approaches that have been employed as a means of assessing the risks associated with failure of these services as a consequence of climate change scenarios.

The aim of this review is therefore to establish an understanding of the latest techniques used in quantifying impacts from hazards that pose risk to city's infrastructures and services. The goal being to expand on this research to more accurately quantify the risks posed to the cities of Barcelona, Bristol and Lisbon from climate driven hazards, examine how the impacts from these hazards propagate through different services and in doing so help services understand these risks and find means of mitigating them to improve their city's resilience.

1 Introduction

As cities continue to expand and populations of cities continue to grow there is increasing pressures on the city's services. The smooth running of a city generally goes unnoticed and it is only when there is an impact/failure on an infrastructure or service does the complex nature of what is required for the continued smooth running of a city becomes apparent. This document looks at the consequences of different scenarios that can result in the reduction of capacity or the failure of a service or infrastructure therefore affecting the overall resilience of a city. These scenarios could be that of natural phenomena such as flooding, heat wave, cold-wave etc.; man-made such as accidental contamination of reservoir, act of terrorism on infrastructure, or human error; or technological failure. RESCCUE project will focus only to social and economic impacts produced by natural hazard for current and future scenarios. As a simplistic fictitious example, Figure 1 shows a simplified power supply network providing electricity to houses and two hospitals. In this example there are three services (Power Generation, Power Distribution and Health Care) being considered. Within the power distribution setup two types of infrastructure (Power Lines/Pylons, and Substations) are considered. The Health Care service in this instance consists of two Hospitals. If one of the substations was to fail (e.g. failure due to damage from a flood event) the Health Care service could be affected, if the emergency backup options have been exhausted. Table 1 shows the effect on infrastructure and services. This simple example shows that the effect on a service and infrastructure due to component failure is dependent upon where this failure is to occur. In this instance failure at substation A would have the most detrimental effect, therefore if flooding was one of the most frequently occurring events in this fictitious example it would logically make sense to invest in protecting substation A. Unlike this example, however, the reality of interdependencies between services and infrastructures within cities is both far more complex and subsequently far more obscure to the casual observer. This complexity is not just solely to do with the complicated spatial distribution of infrastructures throughout the city but also the complex and often obscured interdependencies between services and infrastructures.

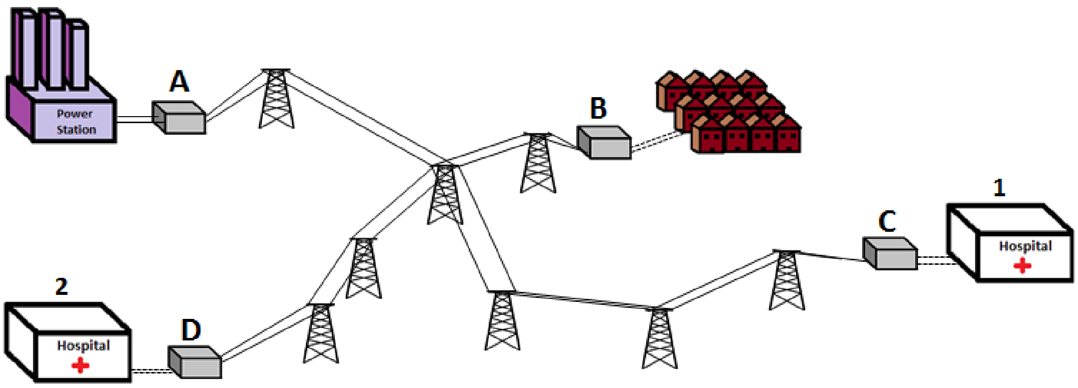

Figure 1: Simple example of power supply chain to hospital service

Table 1: Health Care Service Status based upon prolonged power supply disruption

Impacted Transformer	**Health Care Service Status**	**Hospital 1 Infrastructure Functionality Status**	**Hospital 2 Infrastructure Functionality Status**
A	Down	Down	Down
B	Unaffected	Unaffected	Unaffected
C	Reduced Service	Down	Unaffected
D	Reduced Service	Unaffected	Down

1.1 Definitions

Various complex terms are used within this document including service, infrastructure, impact, exposure and hazard. The use of these terms can vary within literature but within the context of this document they will be defined as follows.

Direct Damage relates to damage that results directly from a defined impact; for example a flood event could cause direct physical damage to an infrastructure due to the immediate physical contact of flood water with humans, property and the environment. The terms ‘loss’ and ‘damage’ are used synonymously in the literature.

Disaster refers to “severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery" (Field et al. 2012)

Exposure refers to the risk of a service, infrastructure and or population being adversely affected by an impact.

Hazard refers to "the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources" (IPCC 2012). A hazard could, for example be a flood event, coldwave, heatwave, risk of terrorism and/or cyber-attack.

Impact refers to the effect/influence of an event (naturally occurring or manmade) that results in a consequence such as causing damage and/or disruption to a service or infrastructure. An example of an impact could be a flood event causing damage to an energy substation resulting in a localised power cut. The term '**impact**' refers to the broad effects that an event can have on people, to property and to the environment. These impacts can be both positive and negative, although it is common in the literature to see the term used in a purely negative sense, especially in relation to human health, where health impact assessments are conducted.

Indirect Damage is induced by the direct impacts and may occur – in space or time – "outside" the event. In the context of this document refers to the detrimental effect on a system.

Infrastructure refers to physical buildings and objects that provide or facilitate the distribution of a service. Again in the example of "Energy Supply" an infrastructure could be a power station, power lines, power substation etc. and in the context of "Health Care" and infrastructure could be a hospital, clinic, blood bank etc.

Intangible damage refers to damages that cannot be expressed in monetary values, for example the loss of life or the deterioration of health as a result/consequence of an impact.

Resilience is considered as the adaptive capacity of a system to endure any perturbation, like floods, droughts or other hazardous event, maintaining significant levels of efficiency in its social, economic, environmental and physical components; resilience to a hazardous event damages can be considered only in places with past events, since the main focus is on the experiences encountered during and after the events (ISO Guide 73:2009). **Risk** is the probability of harmful consequences — casualties, damaged property, lost livelihoods, disrupted economic activity, and damage to the environment — resulting from interactions between natural or human-induced hazards and vulnerable conditions.

Risk Assessment is "a methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend.

Service refers to something that is provided to the city and/or population of the city to enable it to function. For example, "Energy Supply" is a Service that provides electricity to a city and "Health Care" is a service that looks after the physical and mental wellbeing of a city's population.

Scenario is "a plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships" (IPCC 2012).

Susceptibility (within RESCCUE susceptibility and sensitivity, will act as synonyms) is the degree to which the system is affected, depending on the own intrinsic characteristics of its exposed elements within the area in which hazardous events may occur. These intrinsic properties include, for instance, the physical characteristics of exposed elements (service, infrastructures, etc.), the economic and social context of the community, etc. For floods, for instance, important capacities are the awareness and preparedness of affected people and the existence of mitigation measures to reduce the effects of the hazards, like warning systems and emergency plans (Viseu *et al.*, 2016).

Tangible damage refers to monetary damage that has occurred as a result of an impact.

Vulnerability refers to the propensity of exposed elements (such as human beings, their livelihoods and assets) to suffer adverse effects when impacted by hazard events. Vulnerability is related to predisposition or capacities that favour, either adversely or beneficially, the adverse effects on the exposed elements. Vulnerability refers to exposure, susceptibility and resilience (BINGO, 2016).

1.2 Typology of damage

To understand the damage or losses that an impact can cause, it can be useful to categorize them. Within the literature, there is a broad consensus on the categorization of damage. The first distinction that is commonly made is between tangible and intangible damage. A tangible damage is a damage that is capable of being assessed in monetary terms (Smith and Ward 1998). A similar but slightly different definition is given by Messner *et al.* (2007), who define a tangible damage as one that can be "easily specified in monetary terms".

The second common distinction is between direct and indirect damage. Typically, a direct damage is defined as any loss that is caused directly by an event naturally occurring or manmade. In case of flooding, for example, a direct damage is defined as any loss that is caused by the immediate physical contact of flood water with humans, property and the environment. An indirect damage is induced by the direct impacts and may occur – in space or time – outside the flood event.

In the framework of CORFU project (Collaborative Research on Flood Resilience in Urban areas), the following categories (Table 2) were established following previous references of other authors (Messner *et al*. 2007 and Jonkman *et al*., 2008). Although this categorization was elaborated for floods damage, it can be extrapolated to other types of impacts (events naturally occurring or manmade).

Table 2: Categories of flood damage, after Messner *et al*. (2007) and Jonkman *et al*. (2008).

	Tangible	**Intangible**
Direct	Physical damage to assets • Buildings • Contents • Infrastructure • Agricultural land Evacuation and rescue operations Clean up costs	Fatalities and injuries Diseases Historical and cultural losses Loss of ecological and environmental goods Inconvenience
Indirect	Loss of industrial production Traffic disruption Emergency costs Temporary housing of evacuees	Societal disruption Increased vulnerability of survivors Undermined trust in public authorities Psychological trauma

The indirect damages are a cascading effect of the direct damages. The indirect damages try to assess how the direct damages are spread across the closer economic agents. According to Cochrane (2004); Messner *et al*. (2007); Jonkman *et al*. (2008) Hammond *et al*. (2014); Balbi *et al*. (2013) some of the methods in which these models are based on are:

- Post-event economic surveys
- Input-output models (I-O)
- Computable general equilibrium (CGE)
- Integrated economic models
- Regional econometric models
- Linear programming- optimization models
- Benefit transfer

However, a new methodology to assess indirect damages was developed within the PEARL project due to a compromise between accuracy and ease of use is not find within the existing models. Thus, in the PEARL project the model developed is an econometric model but using land use data to improve the accuracy of the methodology. The results are shown in D6.2 of PEARL project (Gruhn *et al.* 2017), while validations will be done during the last year of the project in several case studies.

2 RESCCUE Framework for risks/impacts assessment

According to a classical social based risk approach, the risk can be defined as the combination of the hazard likelihood and the vulnerability of the system referring to the propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events.

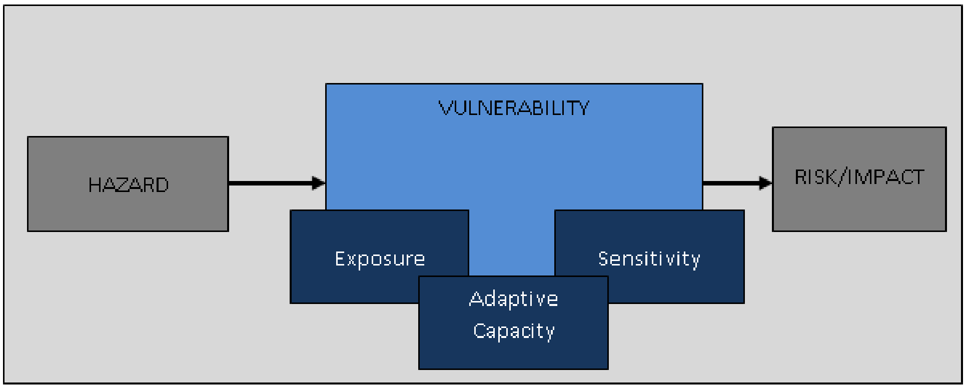

Figure 2: Hazard, vulnerability and risk (based on Turner, 2003 and BINGO 2016).

In this framework and according to Figure 2 and Figure 3, vulnerability is related to exposure, susceptibility and resilience of the exposed system to cope with and adapt to extremes and non-extremes events.

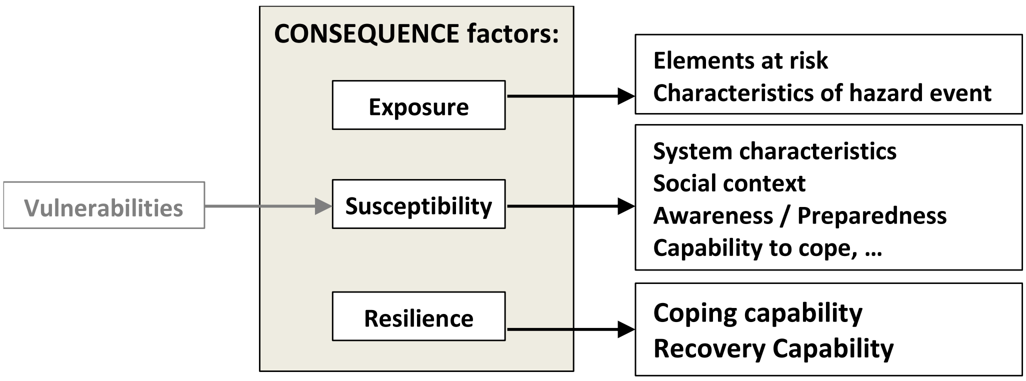

Figure 3: Factor affecting vulnerability concept (BINGO, 2016).

In a broader point of view, focused on the impacts on urban services and the whole city, the impact framework looks at four areas: Hazard, Service, Impact and Consequence (Figure 4). This process/framework is circular based around the approach defined by Butler *et al.* (2016) as part of their work on the Safe & SuRe Project. The four areas are described following.

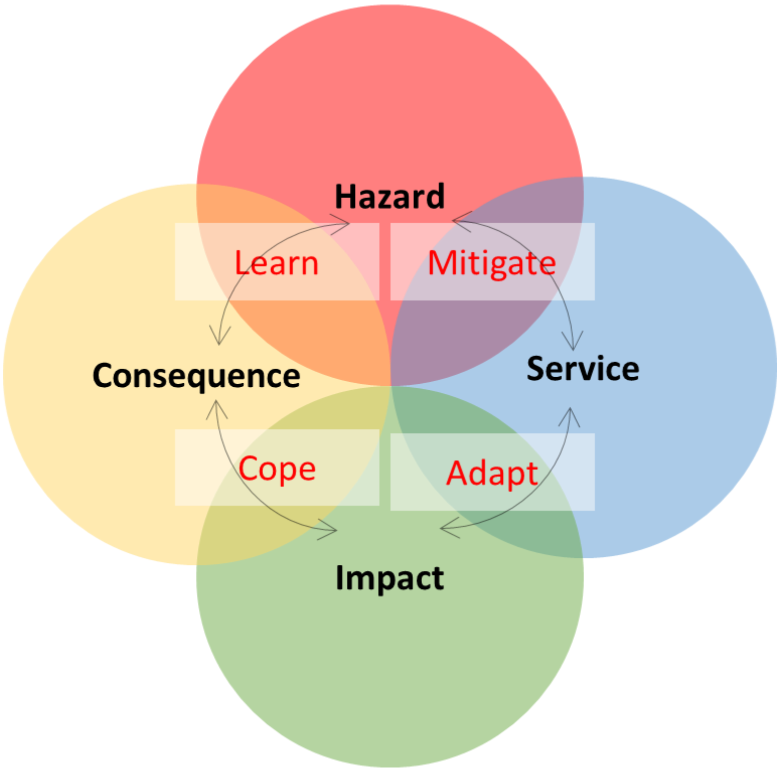

Figure 4: Circular process for the impact/risk assessment on urban services.

Hazard → Service: A given service may be at risk of being impacted by a Hazard. To try to prevent an impact a service may take steps to reduce the level of impact. For example a number of properties in the past have been flooded and are at high risk of flooding again. In an attempt to mitigate this risk, the local council has invested in installing a number of flood defences in the city.

Service → Impact: It may be impossible to fully remove all the risks a hazard poses to a service and as such a service may be still taken offline or be forced to run at a reduced capacity as a result of an impact. In the event of such an occurrence what systems are in place to adapt to the situation? i.e. if there is a power outage at the hospital due to electrical failure, can backup generators be brought online to restore power temporarily.

Impact → Consequence: The effect of an impact may lead to tangible or intangible damages. How does the city cope in the event of a service going offline or being at reduced capacity needs to be considered.

Consequence → Hazard: What can be learnt by examining the consequences of a hazard? From this what can be done to reduce these consequences in the future?

This circular approach of how a city mitigates, adapts, copes and learns from events is indicative of resilience of a city. The following example taken from (Butler *et al*. 2016) emphasises the benefits of a circular based approach to resilience. One of the predicted consequences of climate change is that of increased flood events. A long-term mitigation action to this increased threat would be the reduction of greenhouse gas emissions through policy implementation. This mitigation alone will not however eliminate this threat so city service providers are implementing strategies such as water retention tanks and increase sewer capacities to minimize the impacts. This still will not remove the risk completely and coping actions are required such as emergency planning response and community support would also be required. Even with all this in place there will still, undoubtedly be negative impacts from the flood events and it these which can be learned from to understand where the weaknesses in the resilience design have occurred and thus move through the cycle again.

RESCCUE is aiming to build up a framework that will thus enable cities to evaluate and improve their resilience through the design and integration of software tools. In contrast to reactive approaches it is envisioned that through multi-scenario modelling with respect to climate change scenarios a more proactive approach will be utilised. The creation and implementation of hazard based models within a city along with means of establishing interdependencies between critical services and infrastructures will allow for an effective means of testing and improving its resilience via testing the city against vast numbers of different scenarios.

3 Review of impacts on services

The RESCCUE project is looking at the resilience of cities by (in part) investigating effect of impacts over five primary thematic areas that constitute key services of a city:

1. Water Cycle
2. Energy
3. Transport
4. Telecommunications
5. Waste

Each of these areas are susceptible to a variety of hazards, both manmade and climate driven and the level of impact a hazard/event has on each service will vary. For example, a study carried out by Adams *et al*. (2004) for the US General Services Administration (GSA) looked at the potential climate related impacts on the telecommunications sector derived an impact matrix (Figure 5). This showed the risks of certain hazards (H = High, M = Medium, L = Low, and U = Unknown) have on different aspects of the Information and Communication Technology (ICT) sector, where *D* = Damage and *P* = Probability.

ICT INFRASTRUCTURE AFFECTED	High temp		Low temp		Water table rise		Sea level rise		Storm surge		Prolonged rainfall		Flood		Drought		Snow		Extreme wind		Electric storm		Frost		Fog		Soil shrinkage	
	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P
Telephone exchanges	L	L	L	L	H	U	L	L	L	L	L	L	H	U	L	L	L	L	L	L	H	L	L	L	L	L	L	L
Telephone poles	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	M	M	H	M	H	L	M	M	L	L	L	L
Satellite earth stations	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	M	M	H	M	M	L	L	L	L	L	L	L
Mobile base stations	M	L	L	L	U	L	L	L	L	L	L	L	L	L	L	L	M	M	M	L	M	L	L	L	L	L	L	L
Data centres	M	M	L	L	H	U	U	U	U	U	U	U	H	U	L	L	L	L	L	L	M	L	L	L	L	L	L	L
Satellite-comms	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Satellite-gps	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	U	L	L	L	L	L	L	L
Buried cables	L	L	L	L	U	U	L	L	L	L	L	L	U	U	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Ducts	L	L	L	L	U	U	L	L	L	L	L	L	U	U	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Terrestrial RF comms	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	M	L	M	L	U	U	L	L	L	L	L	L
Submarine comms	L	L	L	L	L	L	U	U	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Private infrastructure	U	L	L	L	U	U	U	L	L	L	L	L	M	L	L	L	L	L	L	U	U	L	L	L	L	L	L	L
Core network	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

Figure 5: Impact matrix on telecommunications service (Adams et al. 2004)

A similar approach was carried out within RESCCUE as part WP2 whereby the three test case cities were surveyed. Table 3 gives a summary overview (taken from WP2) of the impacts on services due to climate related hazards.

Table 3: Summary table of climate based hazards and their impacts on services

<table>
<tr><th>Urban Services</th><th>Subservice Function</th><th>Climate Variable</th><th>Hazard Description</th><th>Impact</th></tr>
<tr><td rowspan="8">Water Cycle</td><td rowspan="6">Water Abstraction/ Storage</td><td rowspan="2">Rainfall</td><td rowspan="2">Flood</td><td>Equipment Failure</td></tr>
<tr><td>Reduced water quality</td></tr>
<tr><td rowspan="2">Temperature</td><td rowspan="2">Drought</td><td>Reduced water availability</td></tr>
<tr><td>Reduced water quality</td></tr>
<tr><td colspan="1">Storm surge and/or sea level rise</td><td>Flood</td><td>Equipment failure</td></tr>
<tr style="display:none"></tr>
<tr><td rowspan="2">Water Treatment</td><td rowspan="2">Rainfall</td><td rowspan="2">Flood</td><td>Equipment Failure</td></tr>
<tr><td>Reduced water quality</td></tr>
</table>

		Temperature	High or Low (outside optimum range)	Reduced water quality
		Storm surge and/or sea level rise	Flood	Equipment failure
	Water Distribution	Temperature	Low	Pipe burst
			High	Increased water demands
		Rainfall	Flood	Equipment Failure
		Storm surge and/or sea level rise	Flood	Equipment failure
	Urban Drainage	Rainfall	Flood	Drainage system over capacity results in flooding
		Storm surge and/or sea level rise	Flood	Drainage system over capacity results in flooding
	Wastewater Treatment	Rainfall	Flood	Reduced water quality
		Temperature	High or Low (outside optimum operating range)	Reduced water quality
		Storm surge and/or sea level rise	Flood	Reduced water quality or Equipment failure
Energy	Power Generation	Temperature	High or Low	Increased demand
		Rainfall	Flood	Equipment failure
		Storm surge and/or sea level rise	Flood	Equipment failure
	Power Transmission	Temperature	Low	Equipment failure
		Rainfall	Flood	Equipment failure
		Wind	High	Equipment failure
		Storm surge and/or sea level rise	Flood	Equipment failure
Transport	...	Temperature	Low (or extreme snowfall)	Road network disruption

		Rainfall	Flood	Road network disruption
		Wind	High	Road network disruption
		Storm surge and/or sea level rise	Flood	Road network disruption
Telecommunications	…	Rainfall	Flood	Equipment failure
		Temperature	High	Equipment failure
		Wind	High	Equipment failure
		Storm surge and/or sea level rise	Flood	Equipment failure
Waste	…	Temperature	Low (or extreme snowfall)	Disruption to collections
		Rainfall	Flood	Equipment failure
				Pollution
		Wind	High	Damage
				Pollution
		Storm surge and/or sea level rise	Flood	Equipment failure
				Pollution

4 Impacts from Hazards

The four primary climate related hazards identified as part of WP 2 were: Rainfall, Temperature, Wind, and Storm Surge and/or Sea level rise. The services that have been identified to be impacted by these hazards are outlined in Table 4. This table helps to highlight that certain climate related hazards affect significantly a number of services.

Table 4: Services impacted by defined hazards

Hazard	Impacted Services
Rainfall	Energy Telecommunications Transport Waste Water Cycle
Temperature	Energy Telecommunications Transport Waste

	Water Cycle
Wind	Energy Telecommunications
Storm Surge or Sea Level rise	Energy Telecommunications Transport Waste Water Cycle

The rest of this section looks at the methods employed in previous research as a means of quantifying the impacts from each of these hazard types on each service.

4.1 **Rainfall**

One of the most common hazards that leads to impacts on services within the cities being studied in RESCCUE is that of flooding, this section gives a summary look of pluvial flooding impacts as a result of intense rainfall events.

4.1.1 Rainfall Impacts on Water Cycle

Ensuring the services that constitute the water cycle within a city is of major importance. A technical report by the Energy Networks Association (2009) stated that some of the most critical services dependent on energy supply are: **water supply**, **sewage treatment** and **land drainage** as failure of these services has the potential to require mass evacuation.

4.1.1.1 Rainfall Impacts on Urban Drainage

The management of wastewater and stormwater within a city can be regarded as impact driven. Urban drainage systems are purposefully designed to cope with weather related impacts as a means of protecting persons, contents and infrastructures from weather based events. Over recent years, there have been numerous studies looking into the impacts of flooding around the world. Hammond *et al*. (2015) conducted a comprehensive review of methods for urban flood assessment covering areas such as the relationship between flood impact assessment and resilience, direct tangible damage in the form of physical damage to property and contents along with indirect tangible damage associated with loss of business.

The management of wastewater and stormwater flows can be looked at from two perspectives: on the surface and underground. These are commonly assessed respectively via 2D Surface Flow and 1D Sewer Network modelling which can be coupled together (1D/2D coupled model). The modelling of surface flow within cities is commonplace and there are a variety of industry standard software packages used for doing so such as TUFLOW[1] or HEC-RAS[2] to name a couple of examples. These use complex Shallow Water Equations to accurately simulate the movement of water over a surface. Recent research by Guidolin *et al*. (2016) and Gibson *et al*. (2016) has looked at using a more computationally simplified approach Cellular

[1] http://www.tuflow.com/

[2] http://www.hec.usace.army.mil/software/hec-ras/

Automata (following CA) approach for rapid flood modelling. This model (CADDIES) used simple transition rules and a weight based system as opposed to the more complex Shallow Water Equations. The studies showed that CA based methods can still maintain a level of accuracy akin to that of the industry standard models used for benchmarking whilst running order of magnitude quicker.

When modelling the effectiveness of drainage infrastructure, a more simplified 1D approach can be implemented whereby the movement of water is restricted along that of the pipe network. These 1D models can be coupled with 2D surface flow models to create more realistic representations of flood events within a 1D/2D coupled model (1D for underground sewer network model and 2D for overland flow) (Seyoum *et al*. (2012) and Leandro *et al*. (2009)). The interactions between the two drainage layers (known, respectively, as 'major system' formed by streets, sidewalks, squares, etc. and 'minor system' formed by the sewer network) occur through the surface drainage system formed by street inlets and also through manholes in case of overflows produced by surcharged pipes.

Recent events have shown the importance of stormwater management in regards to the link between the surface and the drainage network and the routing and management of surface flow. In September 2012 a flood event in the town of Filton resulted in the flooding of the National Health Service Blood Transfusion's (NHSBT's) site within that town. NHSBT in Filton is the largest blood manufacturing facility in the world, with more than 600,000 donations processed there each year. It serves 90 hospitals across the Midlands and the South West[3]. The cause of the flooding was attributed to that of a blocked culvert (Rackham & Lawson, 2013). Research by Gómez *et al*. (2013) looked at the issues that arise as a result of reduced stormwater drainage capacity due to inlets becoming blocked with debris; and a more recent flood event (due to the arrival of storm Angus in November 2016) at Whitchurch road in Bristol has been attributed (in part) to reduced drainage capacity as a result of inlet blockages. In Barcelona they anticipate that due to the increase in both frequency and intensity of rainfall events with downpours doubling in frequency and peak rainfall rates being up to 20% higher (Ajuntament de Barcelona 2013) with further work by Rodríguez *et al*. (2014) further highlighting this trend in increased rainfall intensities due to climate change predictions. This increase in rainfall intensity could lead to the systems in place for the management of wastewater being overwhelmed resulting in pluvial flooding.

Traditional 1D models are unable to adequately describe flooding in urban areas and detect the causes producing these problems (for example great runoff volumes not conveyed into the sewers coming from upstream catchments or the flow interchange between sewers pipes and streets). Even if it is clear that the choice between using a 1D surface network model or a 2D surface system model determines the accuracy of results and the computational time required to obtain them, when the flow overtops the curbs in the streets and it does not remain within the street profile, using a 2D model is crucial (Mark *et al*. 2004).

Recently several authors published interesting papers treating the need of coupled approaches (modelling of the surface and sewer flows at the same time) to represent

[3] http://www.bristolpost.co.uk/blood-bank-moves-stock-building-hit-floods/story-16987446-detail/story.html

adequately urban flooding caused by sewer overflows (Phillips *et al*., 2005; Lipeme Kouuyi *et al*., 2008; Obermayer *et al*., 2010; Leandro *et al*., 2009) and carry out a realistic flood risk assessment (Kandori and Willems, 2008). Currently, a 1D/2D coupled model represents a powerful tool to describe, in a very realistic way, the hydraulic behaviour of urban areas suffering flooding problems due to the excess of runoff not conveyed by the drainage networks and to quantify social and economic flood impacts. Recent advances in hardware and software allow the use of this type of modelling for extensive areas. For Barcelona, in the framework of CORFU project, the half of the city was modelled using a detailed 1D/2D and the computation time was drastically reduced using multiple CPUs and a specific Graphic Card (Russo *et al*., 2015).

In the framework of RESCCUE, Barcelona and Lisbon will employ 1D/2D modelling approach to estimate hazard in flood prone areas in order to achieve detailed flow information to be used to quantify social and economic flood impacts. Moreover, as part of the Flood Modelling strategy for RESCCUE, the University of Exeter is going to carry out additional modelling using in house software including the UIM (Urban Inundation Model) and also utilise CADDIES (Cellular Automata Dual-DraInagE Simulation).

The Urban Inundation Model (UIM) is a 2D finite difference based model that uses non-inertia flow equations and like other 2D models the simulation of overland flow is quite computationally demanding (Chen *et al*. 2007). As a means of reducing computational time whilst maintaining accuracy the UIM allowed for building to represented within coarse scale grids by their Building Coverage Ratio (BCR) (percentage of occupancy) and the restricted movement of flow between coarse grid cells by their Conveyance Reduction Factor (CRF). This work was later expanded upon to depict more complicated building layout scenarios in multiple layers. This approach allows for more realistic representation of surface flow by allowing for the capture/representation of coarse grid cells that may be bisected by a building (Chen *et al*. 2012). The CADDIESs approach uses a more simplistic rule based way of representing surface flow and as such produces results quicker than that of the UIM (though it doesn't currently facilitate a multi-layer approach). In this instance the movement of water from one cell to the next is dependent on the conditions of the immediate neighbouring cells using a Vonn Neumann grid (Figure 6). This rule based approach is computationally less demanding than physical based models. Figure 7 shows the flood depth outputs taken from the CADDIES approach (b-c) at various time steps in comparison to flood depths derived via Inforworks (a). For the Infoworks case the computational runtime was 19m 47s whereas for CADDIES cases b-c where the time steps were 0.01s, 0.03s, and 1s respectively the run times were 3min 33s, 1m 46s, and 15s. Due to the computational efficiency of the CADDIES software it allows for multiple scenarios to be tested within relative short time frames.

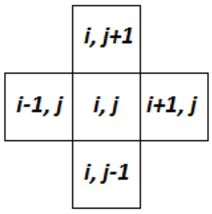

Figure 6. Vonn Neumann grid configuration

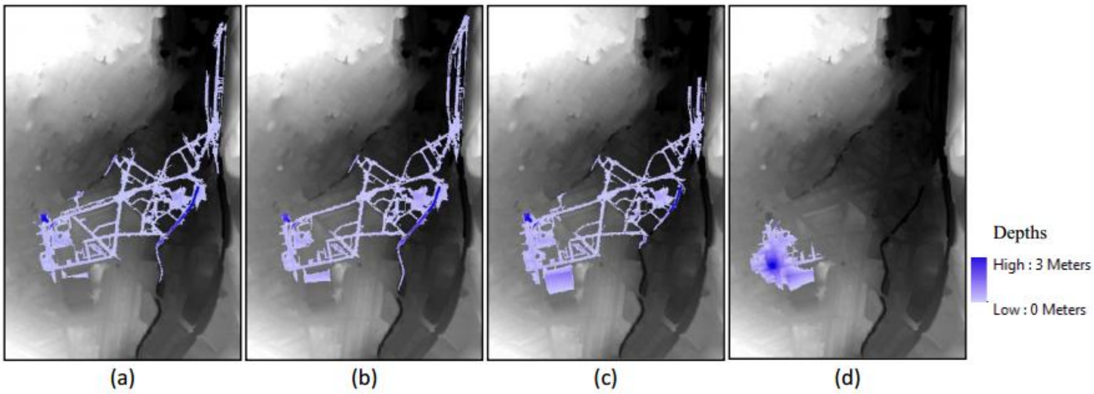

Figure 7. Comparison of CADDIES approach at varying time steps [b-d] against Infoworks approach [a] (Gibson, et al., 2016)

One area of interest within the Bristol case study is to look at the impact of blocked drains from leaf litter or other debris. Previous work by Gómez *et al*. (2013) and Russo *et al*. (2015) has highlighted the effects these blockages have on the drainage system and the potential increases in flood risk due to these events. The CADDIES software has the ability to represent drainage spatially via setting infiltration rates for the removal of water from the surface, the University of Exeter would therefore like to utilise this to simulate various scenarios of drain blockage events for the Bristol research site which could help the local authorities understand the importance and effectiveness of the urban drainage system and assess whether their monitoring/maintenance of the drainage system is effective both in costs and managing risks. This interesting issue will be also treated and analysed for the Barcelona research site, where inlet hydraulics will be estimated to regulate flow interchange between sewer and overland flows. In this case, specific clogging factors obtained during previous field studies (Gómez *et al*., 2013) could be used.

4.1.1.2 Rainfall Impacts on Water Abstraction

High intensity rainfall events that lead to overland flow and/or flooding and one of the more serious consequences of flooding can be large scale contamination of drinking water. This contamination could be caused by bacteria, sewage, heating oil, agricultural or industrial waste, chemicals and other substances getting into the surface water, groundwater and distribution systems (Sun, et al., 2016). In 2000, the town of Walkerton (Canada) was subjected to one such contamination event whereby the local community was affected by an

E.coli outbreak that killed seven residents and left 2,300 sick. A report by the Public Works Department, the Regional Municipality of Peel (2001) found that contamination was a consequence of a heavy rainstorm leading to contamination of the town well from cattle manure from a nearby farm.

One of the issues with most flooding datasets is that although they provide information as to flood depths, flow velocities, arrival time, duration and risks information, the routes taken by flood water is not often conveyed. Within the context of contamination of water supplies as a result of overland flow the routes of which the water has taken across the surface may be as important as that of the flood depths. A potential means of quantifying the risks of contamination to water supplies would be to therefore flag water that has passed through certain regions that have been attributed to having higher contaminant risks such as farm lands or waste disposal.

4.1.1.3 Rainfall Impacts on Wastewater Treatment

One of the most common impacts on wastewater treatment as a result of climate change is that of increased rainfall intensity. Heavy rain can lead to the increase of pollutant concentrations, floatable materials sediments in grit tanks or primary settling tanks which add increased pressures on the treatment process (Phuong Tram, et al., 2014). Like that outlined in the previous "water abstraction" section the routes that the water has taken again play an important role here as contaminants in the water picked up during overland flow will need to be removed or reduced to safe limits before being released or used for applications. This information coupled with the urban drainage information (1D modelling) could help quantify potential impacts/changes in workloads on wastewater treatment plants.

One of the predicted outcomes of climate change is the occurrence of more "flashier" events whereby there may be relatively long periods of drought followed by a sudden high intensity rain storms. For gravity driven waste removal a sudden rainfall event after a long drought period can lead to "first flush" effect whereby the sudden influx of water leads to increased concentrations of pollutants arriving at the wastewater treatment facility. In other scenarios where there are prolonged periods of continuous (not extreme) rainfall, the opposite effect may occur whereby the concentrations of pollutants present in the water arriving at the wastewater treatment plant would be significantly lower than standard levels and the plant should be capable of adapting to this to increase its performance and to ensure not over-treating the water. In situations where there are prolonged periods of intense rainfall and here the urban drainage system has combined sewer overflows (CSO) there will be increased untreated sewerage discharge directly back into the natural water courses. This can potentially result in contamination of localised and downstream regions from where this discharge occurs and subsequently impact the natural environment and increase risk of contaminating future water supply.

4.1.2 Rainfall Impacts on Energy

Water from intense rainfall events can ingress into high voltage insulators and switchgear that can lead to flashovers and catastrophic failures though this risk can be minimised through maintenance. Although flooding does not pose direct threat to overhead lines it is problematic to ground based switchgear and transformers and if such equipment is submerged it is likely to take weeks to repair or replace (Ward, 2013). Table 5 gives a summary of the types of substations in use in the UK, their approximate number and the number of customers each typically supplies.

Table 5: Electricity Substation Types (Energy Networks Association (2009))

Substation Type	**Typical Voltage Transformation Levels**	**Approximate number in UK**	**Typical Size**	**Typical Number of Customers Supplied**
Grid	400kV to 132kV	377	250m by 250m	200000/500000
	132kV to 33kV	1000	75m by 75m	50000/125000
Primary	33kV to 11kv	4800	25m by 25m	5000/30000
Distribution	11kV to 400/230V	230000	4m by 5m	1/500

The Engineering technical Report (ETR) by the Energy Network Association (ENA) states that the following needs to be considered when looking at the resilience of the energy grid and substations:

1. Identify all substations within flood plains using best available data
2. Establish the vulnerability of each substation to flooding (predicted depths that are likely to cause damage and loss of supply)
3. For each substation "at risk" from flooding, identify the impact (including societal impact)
4. Establish whether the site is or will be protected by a flood protection scheme sponsored by the appropriate local authority

A substation is at risk of being impacted if the predicted flood depths are at the level or above that of the critical components that the substation is comprised of. Figure 8 shows an example of the components of a substation that is located within close proximity to the ground and therefore susceptible to flood risks. For substations in Great Britain, the Energy Networks Association (ENA 2009) advises a target resilience defence level of 1:1000 years, plus 20 % increase in river flow or 300 mm to allow for climate change, plus a margin for data error.

A B

Figure 8: (A) 132kV Grid substation with main power conductor at high level and control circuits located in cubicles at lower level, (B) Cubicle at low level suceptible to flooding (Energy Networks Association (2009)).

It is important to understand the risks of flooding on energy supply due to it being an integral service for a city and the number of critical infrastructures that are dependent upon energy supply. A technical report by the Energy Networks Association (2009) states that some of the most critical services dependent on energy supply are: **water supply**, **sewage treatment** and **land drainage** as failure of these services has the potential to require mass evacuation.

4.1.3 Rainfall Impacts on Transport

A breakdown in the transport infrastructure can bring a city to a standstill. The winter of 2009-2010 in the UK which was the worse in 30 years (Met Office (2016)) brought much of the UK to a standstill and was estimated to have cost the economy £700 million[4]. The following winter of 2010-2011 reduced the UK's GDP by 0.5% and the travel disruptions were estimated costing the UK economy £280 million per day (House of Commons Transport Committee 2011).

Previous work by Pyatkova *et al*. (2015) looked at the impact of flood events on traffic/journey times (Figure 9).

[4] http://news.bbc.co.uk/1/hi/uk/8447873.stm

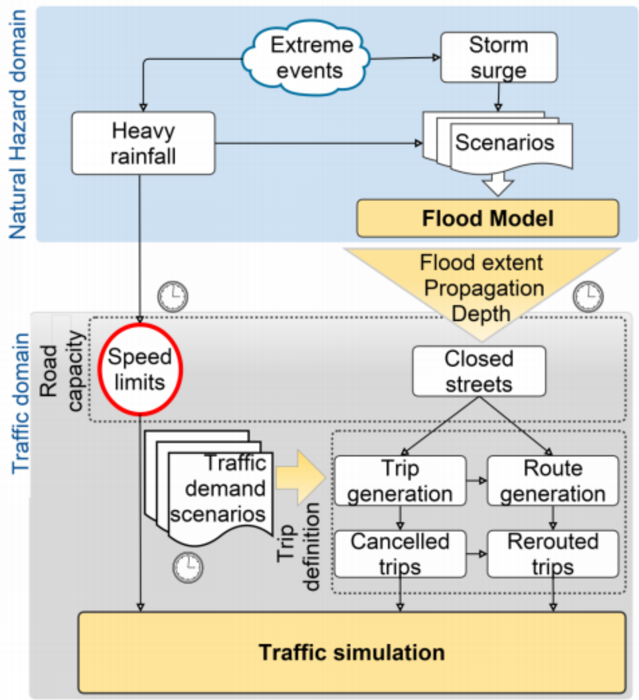

Figure 9. Methodology of linking traffic simulations with Flood Models proposed in PEARL project (Pyatkova *et al*. 2015)

The majority of the traffic models end with non-monetary output. Thus, it is difficult to assess the real impact that traffic models capture. In order to make the traffic outputs comparable and to aggregate them with the other damage outputs, a monetization of the increase in pollution, increase of fuel consumption and increase in time was done in the frame of PEARL project (Gruhn *et al* 2017). Therefore, the methodology does not give a number, a price or an equation to monetize these impacts, but provides recommendations on how to do the assessment and what kind of prices or equations apply.

In the case of fuel consumption as it is a commodity it is recommended to look at the market in the place and time where and when the study is done. In contrast, in the case of increase in pollution and increase in time, an economic monetization technique is needed. Regarding the increase in pollution the methodology used by US EPA is recommended. It is used in several EPA studies and takes into account the whole impact of emitting every tonne of GHG. Finally, for the increase in time the method selected is taken from the Travel Cost Method (TCM), as the time increase is spent travelling. TCM uses a fraction of wage rate, which is found in several examples such as Egan *et al*. (2009), Langemeyer *et al*. (2015) and Jala and Nandagiri (2015).

4.1.4 Rainfall Impacts on Telecommunications

The telecommunications sector can be envisioned as a supply chain map as depicted in Figure 10 which shows its primary inputs and summarised infrastructure. Both the inputs and infrastructure are susceptible to impact from climate driven hazards where failure of one of the components will result in either reduced service performance or a service failure. It is envisioned therefore that due to the predicted increase in severe intensity rainfall events as a result of climate change the frequency of which the telecommunications sector is impacted may also increase (Adams *et al*. 2014).

Figure 10: Supply chain map for the telecommunications sector (by Adams *et al*. (2014))

A literature survey carried out by for the General Services Administration revealed the following in relation to rainfall impacts (in the context of both increased and decrease rainfall amounts) on the telecommunication network (Figure 11). This showed that the impacts of rainfall (and snowfall) on the telecommunications network is experienced both at ground level and above the ground.

Precipitation

- Increased precipitation (rain or snow) leads to a higher risk of flooding low-lying and underground infrastructure and facilities, as well as erosion or flood damage to transport structures, potentially exposing cables (Horrocks et al., 2010; Ofcom, 2010).
- Icing during rain may impact telecommunication lines and infrastructure (ClimAID, 2011).
- Decreased precipitation can lead to land subsidence and heave, which can reduce the stability of telecommunications infrastructure both above and below ground (Horrocks et al., 2010; Garnaut, 2008; Ofcom, 2010).
- Decreased precipitation, in combination with increased temperatures, may increase the incidence of fires, which poses a risk to infrastructure, especially in rural or remote locations (Garnaut, 2008).
- Reduced snowfall may lessen the impact on transmission infrastructure, such as masts and antennae, requiring less upkeep or maintenance (Horrocks et al., 2010; Ofcom, 2010).
- Decreased precipitation may increase seasonal water scarcity, reducing the amount of water available for cooling (BSR, 2011).
- Increased precipitation and humidity can affect the radio spectrum on which wireless communications rely. Rain and snow absorb signals at some frequencies; therefore heavy precipitation can result in some transmitted signals not being received clearly or at all. Some services may also require increased transmission powers in order to withstand poorer weather without experiencing outage. As a result, this could limit the number of users supported in a given spectrum band (Ofcom, 2010).

Figure 11: Climate impacts on telecommunications due to precipitation (Adams *et al*. 2014)

Service performance as result of increased humidity, rainfall and snowfall could be estimated long term wise via climate prediction modelling. The more immediate and consequential impact to telecommunications originates more from the flooding hazard through direct damage to the transmission infrastructure or indirectly via damage to the primary inputs that service telecommunications.

4.1.5 Rainfall Impacts on Waste

The systems in place for the removal of waste are also at risk of being impacted/disrupted by external factors such as severe weather events. Extreme snowfall and icy roads can make some regions within a city become temporarily inaccessible resulting in the local accumulation of waste in regions[5, 6]. Flood events can also result in the movement and deposition of waste in streams and rivers resulting in pollution and affecting biodiversity[7] and within the UK there are over 1000 landfill sites that are at risk to coastal erosion[8].

Poor waste management can contribute to the impact of urban flooding due to drains becoming blocked with debris (Lamond *et al*. 2012). In December 2015 the A8 road in port Glasgow was closed due to flooding with the cause being attributed to that of illegal waste disposal blocking a culvert[9]. Lamond *et al*. 2012 looked at the causes of flood events from a variety of cities as part of their case studies and found that blockages due waste debris occurred in a number of them (Table 6).

Table 6: Summary of flood causes taken from Lamond *et al*. 2012.

Case Study	Identified Problem
Bamako	Poor waste management a major factor in 1999 flood
Accra	Blockage of drainage causes flooding
Cotonou	Indiscriminate dumping of waste
Maputo	Flooding caused by inadequate drainage in the city
Lagos	Flooding due to blocked drainage
Marikina	Flooding partly due to waste clogging the river
Jakarta	Blocked channels cause widespread flooding
Mumbai	Plastic bags blamed for flooding
Guyana	Clogged and inadequate drainage leading to flooding
Mexico City	Waste blocks drains and leads to flash flooding
Managua	Waste in the rivers worsen flooding

As debris within the drainage system can lead to flooding and flooding can lead to the migration of waste into the drainage system there is the potential of a positive feedback loop occurring in the absence of effective waste management (Figure 12). Previous work by Gómez *et al*. (2013) and Russo *et al.* (2015) has highlighted the effects these blockages have on the

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5 http://www.telegraph.co.uk/news/earth/businessandecology/recycling/8236367/Households-left-with-month-of-rubbish-after-snow-and-Christmas-hit-collection.html

6 http://www.bristolpost.co.uk/load-rubbish-8217-s-unhygienic-messy-piling-bristol-streets/story-11307389-detail/story.html

7 https://asiancorrespondent.com/2016/06/trash-yangtze-river-china-flooding/

8 https://www.theguardian.com/environment/2016/may/05/pollution-risk-from-over-1000-landfill-sites-england-wales-coastal-erosion

9 http://www.greenocktelegraph.co.uk/news/14224775.Rubbish_caused_Port_A8_floods/

urban drainage system and the potential increase in flood risk due to these events. The blocking of drain inlets is not limited to that of general man-made waste as natural materials such as that of leaf fall also pose significant blocking effects on the urban drainage system. Massive fall of leaves usually occurs within 7-10 days following a cold episode (Minimum temperature < 6^{o}C for at least 2 consecutive days). This excessive leaf fall can be problematic if it is proceeded by intense rainfall events and removal of leaf litter by the city is thus required to mitigate/prevent flooding events.

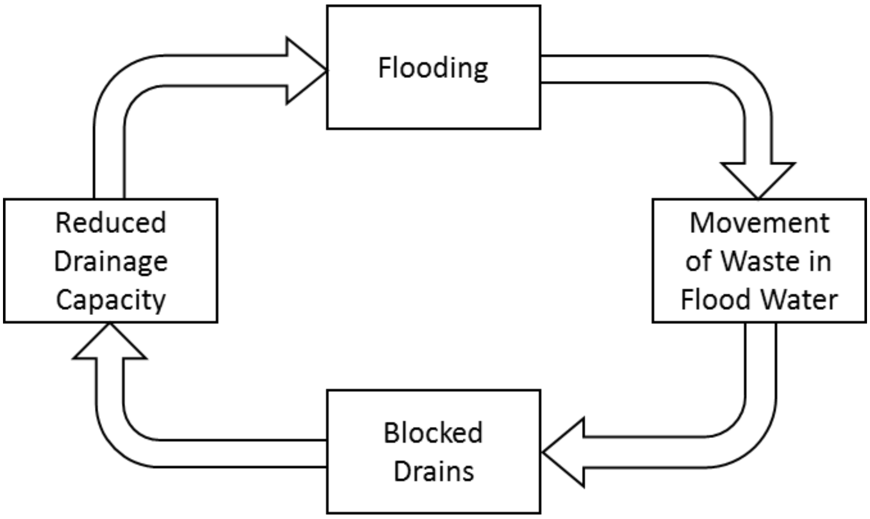

Figure 12: Positive feedback loop of causal relationship of waste on urban drainage system during a flood event

There has been a significant drive recently to reduce the frequency of rubbish collections from weekly to fortnightly to save costs and make residents consider their waste impact more such as in Chelmsford[10], Wolverhampton[11], and Camden in London[12] to name a few. These examples are at a policy level and highlight (in part) some of the financial constraints local authorities have when it comes to waste collection due to cost saving initiatives. Regular periodical collection and removal of waste from cities is essential in order to prevent the spread of disease and infestation along with appropriate methods of disposal. In the context of the impact of waste on the urban drainage system there are increased risks associated with the length of time between waste collections which increases the risk of flooding.

4.2 Temperature

[10] http://www.chelmsfordweeklynews.co.uk/news/14802967.Plansto reduce black bin collection to fortnightly/

[11] http://www.expressandstar.com/news/local-news/2016/10/14/slop-buckets-thrown-out-weekly-bin-collections-scrapped-more-wolverhampton-council-cuts-revealed/

[12] http://www.hamhigh.co.uk/news/environment/almost_half_of_camden_s_residents_to_receive_fortnightly_rubbish_collections_from_april_1_4635018

4.2.1 Temperature Impacts on Water Cycle

As water demand in cities increases, coupled with the effects of climate change, the demand for water is set to grow which results in rising pressures on water supplies. Within the city of Barcelona, current studies indicate the demand for water rising by 5-12% due to a reduction in comfort, increase in evapotranspiration of vegetation, tourism, etc. (Ajuntament de Barcelona, 2013). Changes in temperature such as more extreme variations or long periods of drought also present risks to subterranean pipe infrastructure resulting in potentially more pipe burst scenarios.

4.2.1.1 Impacts on Water Abstraction and Storage

The impacts of droughts and water resources scarcity in the environment are broadly known and studied. However, the translation of the impacts from environment to socioeconomic welfare is less analysed. Some examples of droughts consequences are water and food security (MacDonald, 2010); increased forest fire danger (IPCC, 2012) and impacts on tourism destinations, competitiveness and sustainability (Scott *et al*. 2008).

In Mediterranean countries, droughts can lead to economic damages larger than floods or earthquakes (e.g., the drought in Spain in 1990 affected 6 million people and caused material losses of US$ 4.5 billion; after CRED, 2010). Within Catalonia the number of tropical nights has been growing at an increasing rate since the 1980's with an increase of 1.7 days per decade although this could reach 5 days/decade along the coast and seasonal analysis has shown marked temperature rises in summer with considerable heatwaves (Ajuntament de Barcelona, 2013)

Some institutions establish boundaries to define when a situation is considered a drought or not, and limits whether measures start to be applied. These boundaries are based on critical thresholds of the water reservoirs. In the case of Barcelona, ACA (Catalan Water Agency) is the entity responsible of defining these boundaries (Agencia Catalana de l'Aigua, 2009). These boundaries became very important, because when measures are taken, the impacts start to arise. For example, one of the first measures taken in Barcelona region when droughts occur is to ban swimming pool replenishments, which affect directly in tourism and related activities. These impacts can be assessed through several economic methodologies.

Within the Water Change project (EU LIFE+ Environmental Policy & Governance Programme) several cost benefit analysis were carried in order to classify the benefits of the measures in contrast to the measures costs. In that project, the costs were considered both in the form of capital and operating costs. On the other hand, the benefits were assessed as the benefit of avoided water deficits and the resource costs associated to them. Thus, the benefit was estimated as the difference between the losses assumed in the business as usual situation against the losses in the situation where measures are taken (Guiu *et al*. 2015).

A recent study on the operational resilience of reservoirs in Sardinia by Mereu *et al*. (2016) used System Dynamic Modelling to investigate the issues of supply and demand (Figure 13) of water with respect to climate change scenarios and concluded, based on climate change predictions, the overall inflow to a storage would decrease whereas the demands on that reservoir would increase.

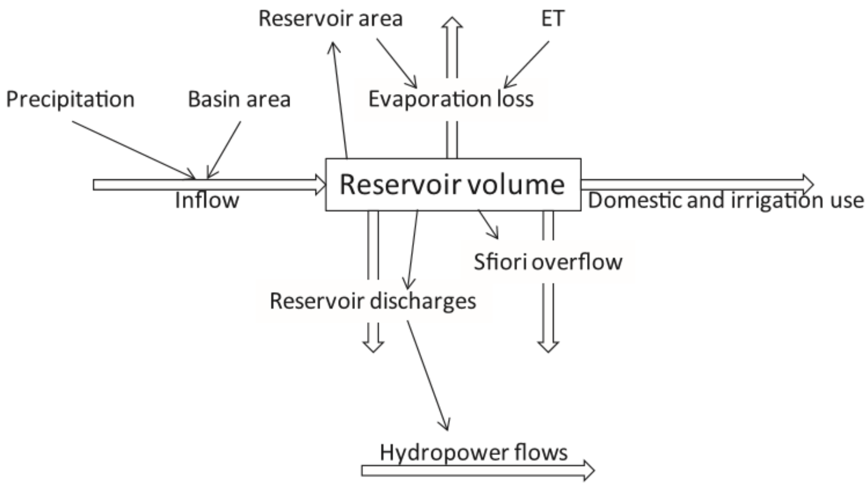

Figure 13: Schematic overview of the systems model for calculation of the reservoir water balance. ET is evapotranspiration. Sfiori is the Italian name for a reservoir over flow structure that is used to control water releases and erosion during flooding events (Meru *et al*. 2016).

In the Sardinia case study, the predicted water demands (shown in Figure 14) were based on two climate scenarios relating to concentrations of greenhouse gasses in the atmosphere (Representative Concentration Pathways (RCP) 8.5 and 4.5 parts per million by volume) and four management approaches are considered: Balanced Competitive and Sustainable Growth (BAL), Business As Usual (BAU), Intensive Tourism Growth (INT), and Strictly Controlled Sustainable Tourism (SOST). The results highlighted that there are changes in water demands for each sector and with water being a finite resource an increase in demand in one sector could cause conflict with the demand from another sector. In this instance in order to compensate for the increased demand for irrigation and domestic use the available supply of water for hydropower is reduced. This overall reduction of available power within cities could prove problematic for services dependent on such power.

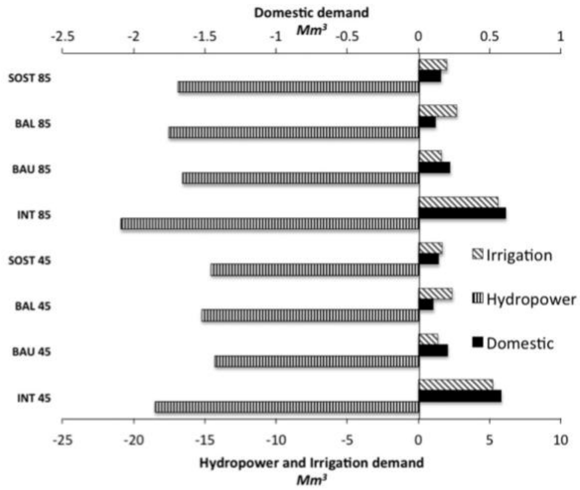

Figure 14: Changes in water volumes in each economic sector relative to the baseline (1960–2000). Note the order-of-magnitude difference in the two x-axis scales. Positive change means an increase in water demand relative to today. Negative change means a decrease. The decrease for hydropower is due to the increases in domestic and irrigation demands. Therefore, there may be water-energy conflicts. (Mereu *et al.* 2016)

Within the city of Barcelona, recent studies indicate a rise in water demand by 5-12% due to a reduction in comfort, increase in evapotranspiration of vegetation, and increased tourism (Ajuntament de Barcelona, 2013).

A study by the Scenarios, Impacts, and Adaptation Measures (SIAM) team predicted that there will be a significant increase in the number of hot days (temperatures greater than 35°C) in the future. It is predicted that with the overall rise in average temperature in Portugal there will be an increase in the frequency of heatwaves and subsequently a decrease in precipitation that will lead to intensification of droughts and greater pressures on water resources (Carvalho *et al*. 2014) (Figure 15).

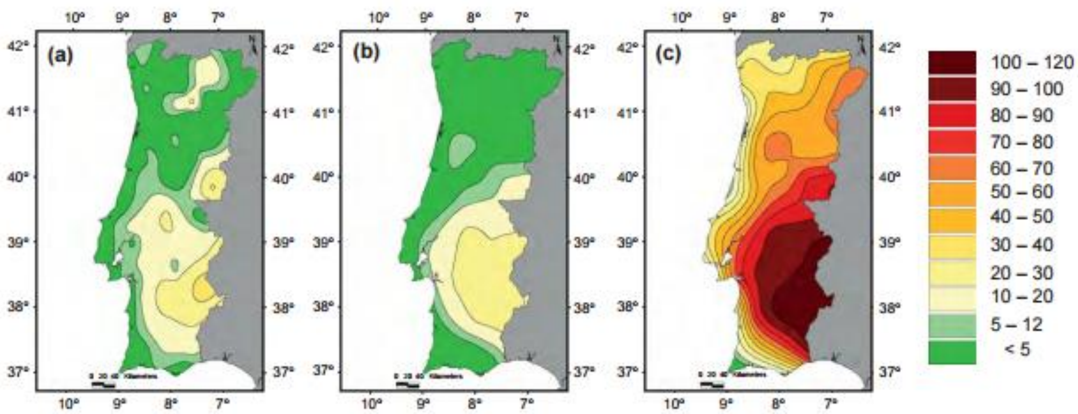

Figure 15: Number of hot days per year with maximum temperature above 35° (summer days) for the (a) 1961–1990 climatology; (b) HadRM2 control simulation; (c) IS92a HadRM2 simulation (2081–2100) - (Carvalho, et al., 2014).

4.2.1.2 Temperature Impacts on Water Distribution

One of the leading causes of failure of the water distribution system is due to pipe bursts. Wols and van Thienen (2016) looked at pipe failure data from the Dutch national pipe failure database and it showed that over a period of 4 years there were 10,325 recorded pipe and joint failures. The effects of a burst water pipe can be quite severe resulting in significant visible damage due to the subsequent flooding or less visible but severe damage over time via underground erosion leading to development of sinkholes. Disruption of the water distribution network is not solely a flood risk problem. Failures in the distribution network such as pipe burst scenarios can result in the loss of water to residential, commercial and industrial regions. One of the causes of pipe burst scenarios is a result of freeze/thaw cycles that causes the expansion and contraction of the ground around pipes placing increased mechanical strain upon them. It is not just a freeze/thaw cycle however that results in ground movement; increased pipe failure rates have been observed during dry summer periods due to shrinkage of soil (Wols and van Thienen 2016) . Figure 16 gives an example approach of how the effects of climate cause varying settlements on soil types and how this can translate into failure probabilities on a water distribution network. It highlights that there is a spatial distribution of increase pipe failure risks that relate to the degree of movement with certain soil types. In addition to the extreme weather variances that are associated with climate change there is the added issue of temperature rise.

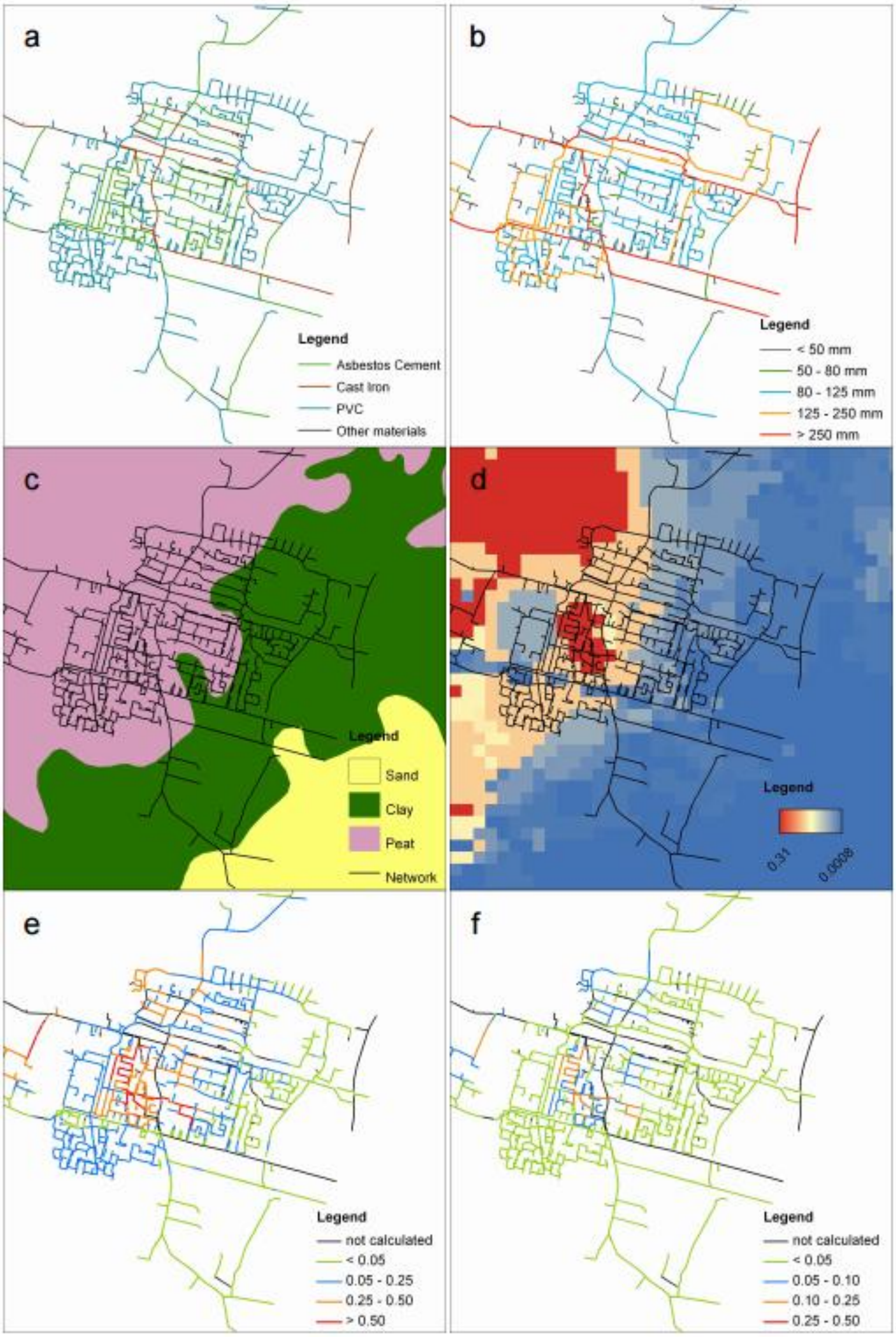

Figure 16: Assessment of the vulnerability of a drinking water distribution network to climate change induced settlements: (a) Pipe materials; (b) Pipe diameters; (c) Soil types; (d) Expected soil settlements; (e) Calculated pipe stresses as a function of yield stress; (f) Calculated probability of failure (Wols and van Thienen 2016).

As highlighted within the "water abstraction" section, the increase in average temperature and heatwave scenarios will cause an increase in the demand for water and as such, there will be increasing pressures on the water distribution network. The rise in ambient temperatures can affect the quality of water within the distribution network. Work by Blokker *et al*. (2016) investigated techniques for mapping water quality within a drinking water distribution system. With temperature being one of the dependent variables for bacterial growth within water there is correlation between the length of time the water is within the distribution network (journey time) and the temperature of the water within the distribution network.

Table 7: Microbial parameters and response to temperature (Blokker *et al*. 2016)

Indicator	**Description**	**Expected Influence of Temperature**
Aeromonas (at 30 ˝C)	Grows in the sediments and biofilm	Positive influence of temperature
Spores of sulphite reducing Clostridia	Used as a process indicator for the treatment works in removal of pathogens No growth	No influence from temperature
E. coli	Faecal indicator, does not grow in the DWDS	No influence from temperature
HPC at 37 ˝C (2 days)	Indicator of bacteria capable to grow at human body temperature	Optimum growth at high temperature, limited influence of temperature in DWDS
HPC at 22 ˝C (3 days)	Indicator for bacteria in water that grow at 22 ˝C	Could grow in the water, possible influence of temperature
HPC at 30 ˝C (5 days)		Optimum growth at high temperature, limited influence of temperature in DWDS
HPC at 22 ˝C (7 days)	Indicator for bacteria in water that grow at 22 ˝C	Could grow in the water, possible influence of temperature

4.2.1.3 Temperature Impacts on Water Treatment

The quality of water pre-treatment is partially dependent on its temperature. Rise in temperatures can result in lower oxygen concentrations in the water, reduce the overall volume of water storage and lead to reduced dilutions of pollutants (Kommunalkredit Public Consulting GmbH, 2013).

4.2.2 Temperature Impacts on Energy

There is an inherent link between energy use and temperature as the city's population looks to maintain their comfort levels be it through heating when the ambient temperature is too cold or conversely though air conditioning if too warm. Therefore there is baseline "comfort temperature" level that people prefer and as you begin to diverge away from that baseline level the demand for energy begins to increase.

4.2.3 Temperature Impact on Transport

Snow and ice on roads poses significant risks to the transportation system and can lead to many roads having reduced capacity (due to reduction of safe driving speeds) or impassable due to snow cover. The winter of 2009-2010 in the UK which was the worse in 30 years (Met Office 2016) brought much of the UK to a standstill and was estimated to have cost the economy £700 million[13]. The following winter of 2010-2011 reduced the UK's GDP by 0.5% and the travel disruptions were estimated costing the UK economy £280 million per day (House of Commons Transport Committee 2011).

4.2.4 Temperature Impacts on Telecommunications

The impact of increased temperatures as a result of climate change on the telecommunication sector is increased pressure on the electrical components themselves as they have an optimum operating temperature range (Figure 17).

Temperature

- Increases in temperature and higher frequency, duration, and intensity of heat waves create an additional burden on keeping equipment cool in exchanges and base stations, resulting in increased failure rates (Horrocks et al., 2010; ClimAID, 2011).
- Increases in mean temperature may increase the operating temperature of network equipment, leading to malfunction or premature failure if it surpasses design limits (Ofcom, 2010).
- Increases in temperature can stress telecommunications equipment and infrastructure, reducing life span (Horrocks et al., 2011; Garnaut, 2008).
- Increases in temperature may lead to an increase in heat-related health and safety risks to workers at telecommunications facilities, as well as at suppliers' sites (Horrocks et al., 2010; BSR, 2011).
- Increased energy demand during heat waves can result in power outages, which can affect the delivery of telecommunications services. Similarly, such disruptions can increase the cost of energy supply (BSR, 2011; ClimAID, 2011).
- Increased temperatures in winter may reduce cost of space heating in assets (e.g. exchanges), creating a cost-saving opportunity (Horrocks et al. 2010).
- Increased temperatures may reduce the frequency of the need to cope with snow-melt water surge (flood) problems in the long term, while in the short term, more rapid melt will increase flooding (Horrocks et al., 2010).

Figure 17: Climate impacts on telecommunications due to temperature (Adams *et al*. 2014)

The "Climate Risks Study for Telecommunications and Data Center Services" report compiled by Adams *et al*. (2014) highlighted a number of direct and indirect climate impacts on the telecommunications service.

Direct climate Impacts:

- Additional burden on cooling equipment from increases in temperature and increased frequency of heat wave events
- Reduction in operational efficiency and increased component failure rates as increases in average temperatures and associated humidity affect baseline design parameters. For example, the loss of ambient cooling potential

[13] http://news.bbc.co.uk/1/hi/uk/8447873.stm

- Conflict between energy efficiency targets and short term spikes or incremental increases in energy demand for cooling purposes
- Increased demand for cooling during heat waves causing power failures in local transmission grids due to excessive loads.
- Increased demand on backup power generators and batteries which have their own environmental impacts e.g. greenhouse gas emissions, hazardous waste.

Indirect climate impacts:

- Restricted supply of (cooling) water during periods of drought
- Restrictions on energy supply due to heat waves and/or drought

4.3 **Wind**

4.3.1 Wind Impacts on Energy and Telecommunications

Parts of the infrastructures in place for the transmission of electricity and telecommunications seperately are in the form of overhead cabling. These overhead lines that span across countrysides and into cities are at risk of being damaged by high winds. Panteli and Mancarella (2015) applied a Monte-Carlo based time-series model as a means of testing the resilience of power systems against HILPs and via the use of fragility curves that provide insight into the likelihood of failure. Here they divide their test area into regions (Figure 18) whereby the weather (in this case probability distribution of wind speeds) experienced within each of the regions differs (Figure 19).

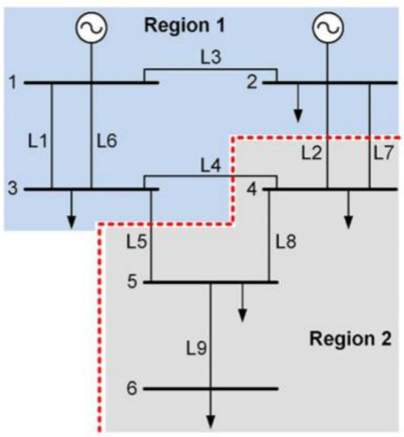

Figure 18. Illustrative example of test system and weather regions

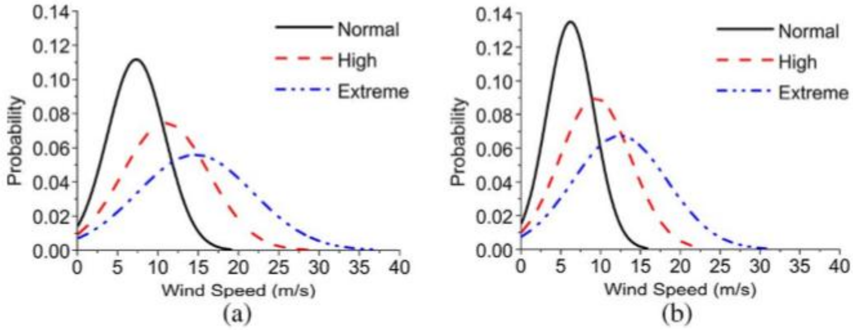

Figure 19: Probability distribution of wind profiles in Region 1 [a] and Region 2 [b] (Panteli and Mancarella 2015)

The likelihood of failure of power line (L1 – L9) or tower (1 – 6) is thus dependent upon its fragility curve which relates failure probability against wind speeds. This regionalised variable approach coupled with fragility curves (Figure 20) relating to the failure of service due to an impact can be expanded upon further to consider the impacts from various hazard types.

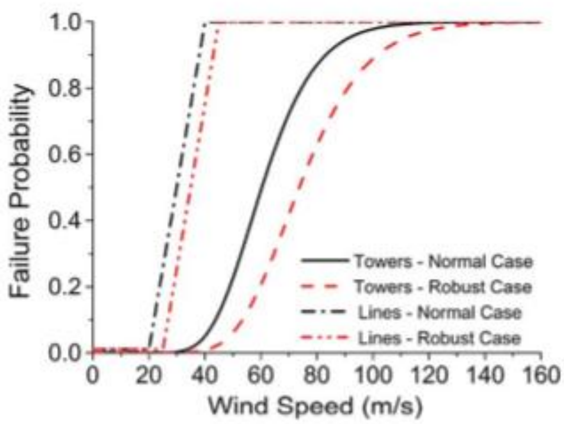

Figure 20: Wind fragility curve of transmission lines and towers for the normal and robust networks (Panteli and Mancarella, (2015))

4.3.2 Wind Impacts on Transport

Wind based events where wind gusts are exceptionally high can have significant impacts on the transportation sector. The impacts from wind may be direct such as making it dangerous for larger vehicles to drive along exposed regions where wind gusts in exposed regions could topple vehicles and indirect due to causing debris to block roads e.g. tree falls, powerline or telecoms line fall. The MET Office in UK utilises a Vehicle OverTurning (VOT) model as a means of quantifying the risk of disruption of incoming windstorms. Figure 21 shows how the VOT data can be visualised coupled with recorded impacts (Hemingway 2016).

4.3.3 Wind Impacts on Waste

Like that outlined in the "Wind Impacts on Transport" section the impacts of wind on waste are both direct and indirect. The indirect effects relate to the disruption of road networks due to high winds. The direct effects result of high winds on waste is that waste can become mobile. In extreme wind scenarios highly mobile waste can pose direct risks to both public and infrastructures due to physical impacts. The additional movement of waste can also result in the pollution of the natural environment.

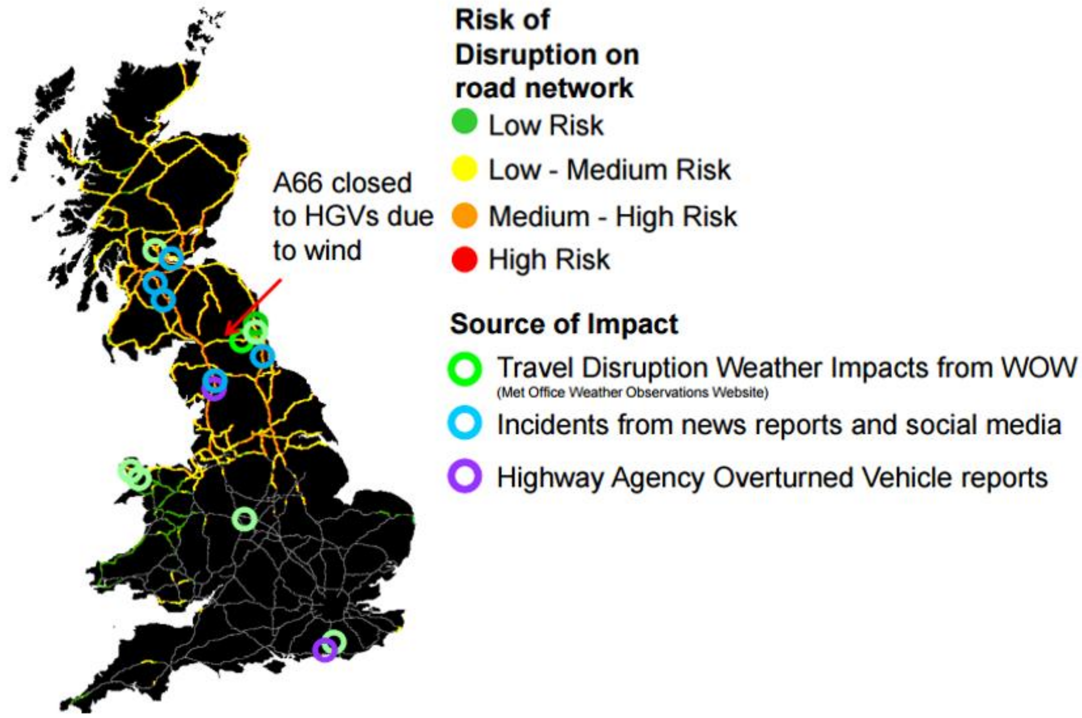

Figure 21: Risk of disruption from wind storm using Met Office VOT model (Hemingway 2016)

4.4 **Sea level rise**

It has been estimated that as a result of climate change that there could be a rise in sea levels around 0.2 m to 1.0 m (Figure 22) by the turn of the next century based on varying Relative Concentration Pathway (RCP) scenarios (Church *et al*. 2013). A comprehensive review of tide gauge data from the Bristol Channel and Severn Estuary taken over a 15 year time period between 1993 and 2007 concluded that there had been a rise in mean sea levels. It had been predicted that there could be a 30 cm increase in sea level by 2050 which lines up with other research and results in relation to UK Climate projections (Hovey and Rodgers 2010).

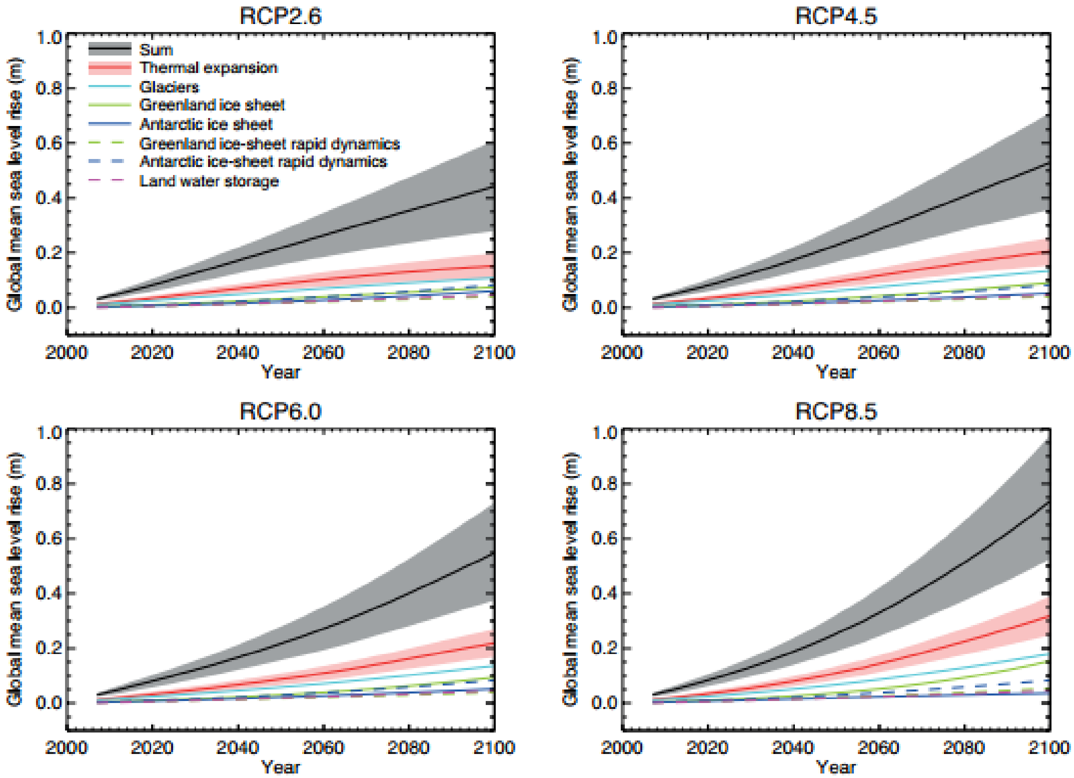

Figure 22: Projections from process-based models of (a) global mean sea level (GMSL) rise relative to 1986–2005 (Church *et al.* 2013)

The implications of changes in sea level are not solely limited direct flooding but there is the additional consequence of land loss through costal erosion. The rise in sea levels presents a major concern for Portugal where coastal erosion is already a significant issue on around 67% of its coastline (Carvalho *et al*. 2014).

4.5 **Storm Surges**

Storm surge pose a significant risk to coastal regions and cities. These surges are normally caused due a combination of driving winds and low atmospheric pressure. Around the UK the size of a storm surge with a 50 year return period is expected to increase by up to 0.9mm/year over the course of this century where the largest projections are predicted to occur in the Bristol Channel and Severn Estuary (Hovey & Rodgers, 2010). Figure 23 shows some of the recorded historical examples of storm surges within the Bristol Channel and Severn Estuary. A study by Sierra *et al.* (2016) on the looking at vulnerabilities of the Catalan region to wave overtopping showed that under current climate conditions, for the worst storm scenarios 23% of the ports are at risk of wave overtopping events. This percentage is predicted to increase up to 47% at risk for the worst future sea level prediction scenarios.

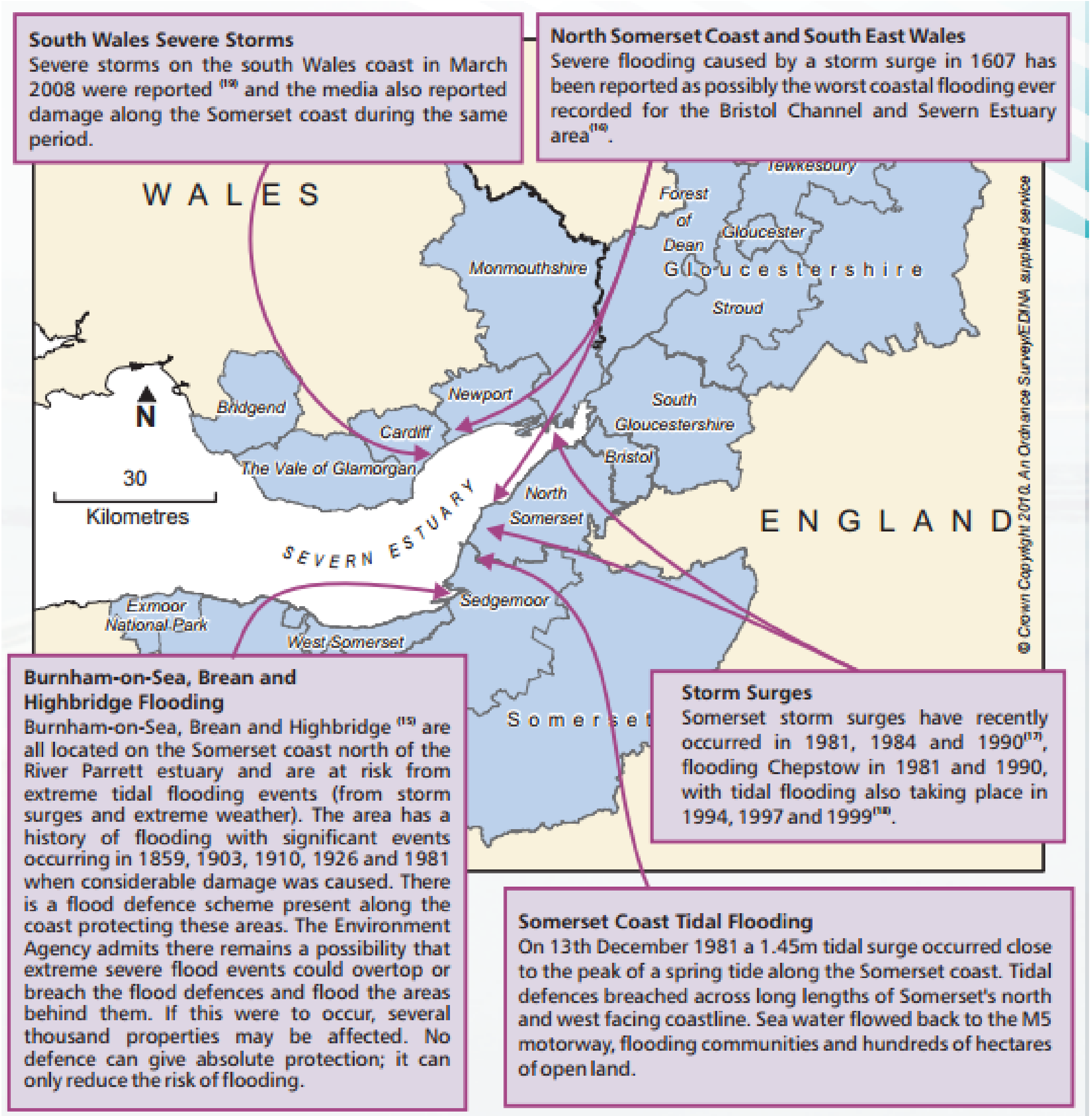

Figure 23: Examples of severe storms and tidal events affecting the Severn estuary (Hovey & Rodgers, 2010)

As mentioned earlier in the "Urban Drainage" sections, the modelling of surface flows from a storm surge event can be simulated using 2D surface flow modelling.

4.5.1 Sea level rise Storm Surge Impacts on Wastewater Treatment

Due to the nature of their operation wastewater treatment plants tend to be at low lying levels and within close proximity to coastlines or large water sources with outflows to the sea to utilise gravity driven techniques for the movement of wastewater. As such they are at inherent risk of exposure to flood based events due to storm surges and rises in sea levels. The impacts on Wastewater treatment plants is not solely limited to direct impacts due to flooding but also indirectly due to changes in the water table resulting in extra pressure on pumping stations. GIS based analysis of the vulnerability of wastewater treatment plants due to their spatial distribution couple with sea level rises based on climate change predictions can be used to reveal/quantify their level of vulnerability. One such method was employed by Friedrich and Kretzinger (2012) in their study on the vulnerability of wastewater infrastructures in South Africa.

5 Common Impact Quantification Approaches

Previous work outlined quantifying the impacts of hazards on infrastructures and services has shown the potential of both damage and fragility curves; whereby damage curves are used to estimate the monetary impacts of a hazard and fragility curves quantify the probability of failure due to a hazard. Figure 24 shows how Damage and Fragility curves fit into the cyclic risk/impact assessment process defined earlier in Figure 4. In this instance if there is spatial overlap between a hazard and an infrastructure that is providing a service and if the magnitude of this hazard in relation to the infrastructures vulnerability is low, then the probability that there will be a service failure will also be low. As the hazard magnitude increases however, the probability of failure also increases and the likelihood of damage can occur.

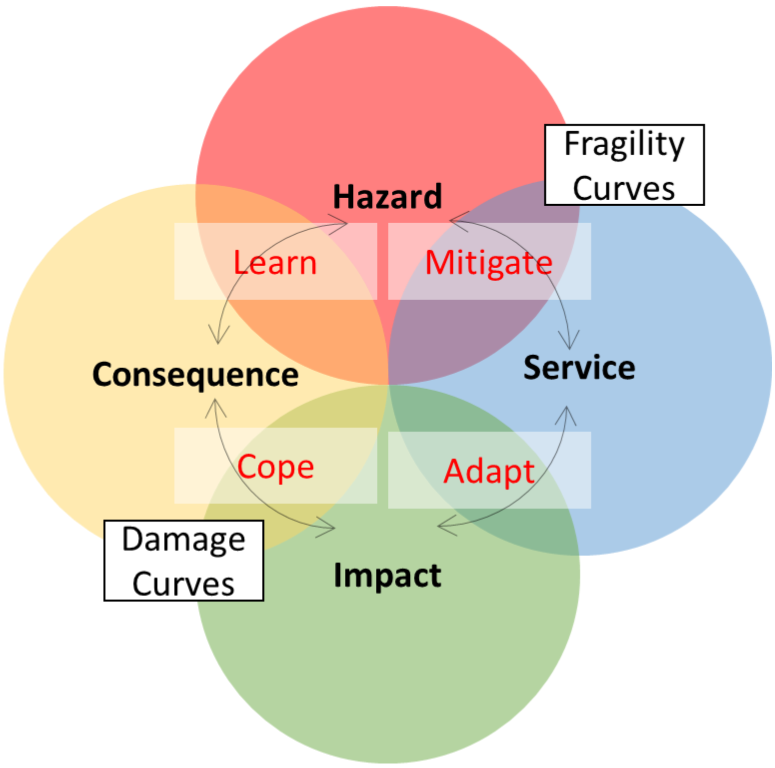

Figure 24: Analysing impacts within the risk/impact assessment process considering damage and fragility curves.

The traditional way in which the impact of a given hazard has on portfolio (collection of properties) is within a catastrophe model that consists of four components: Hazard, Inventory, Vulnerability and Loss (Grossi and Kunreuther 2005) as depicted in Figure 25. Based on information outlined earlier this fundamental model can thus be expanded upon to include further information as to how service losses and damage costs can be quantified (Figure 26).

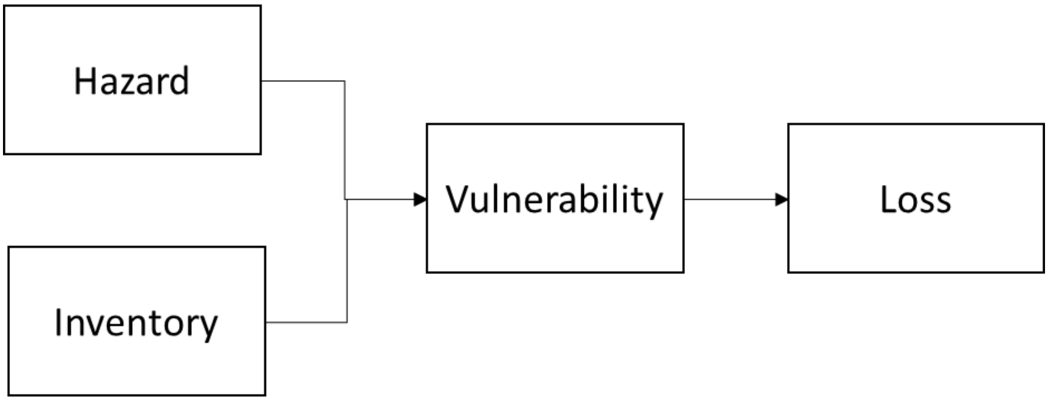

Figure 25: Basic structure of a catastrophe model (Grossi and Kunreuther 2005)

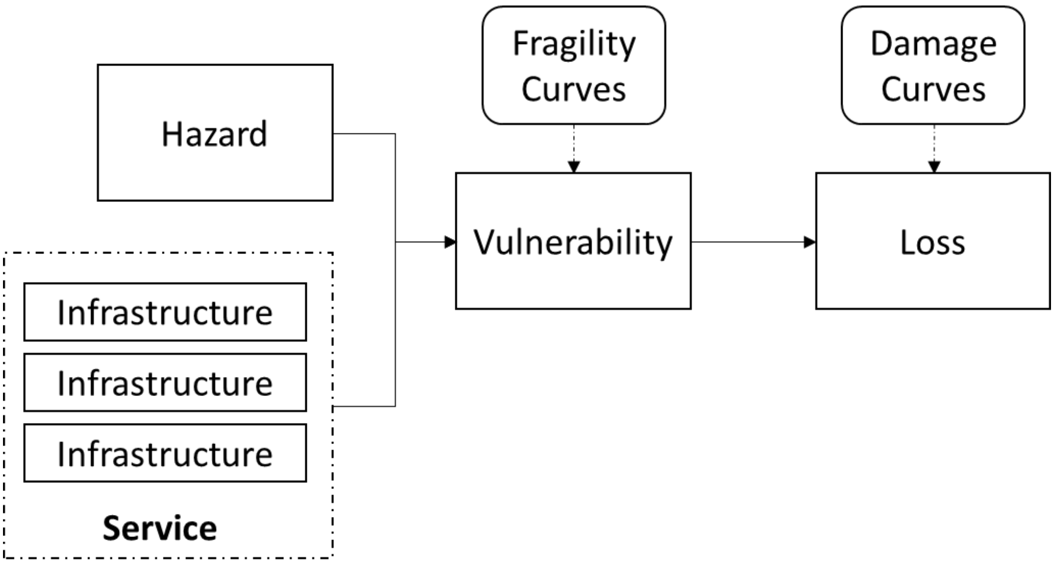

Figure 26: Expanded detail catastrophe model.

Any given hazard can result in both direct and indirect losses. Figure 27 shows a highly detailed version of the catastrophe model within the framework that was designed for the PEARL project in the context of flooding. This framework representation highlights ways in which a flood event can result in both direct and indirect losses through both damage and service interruptions.

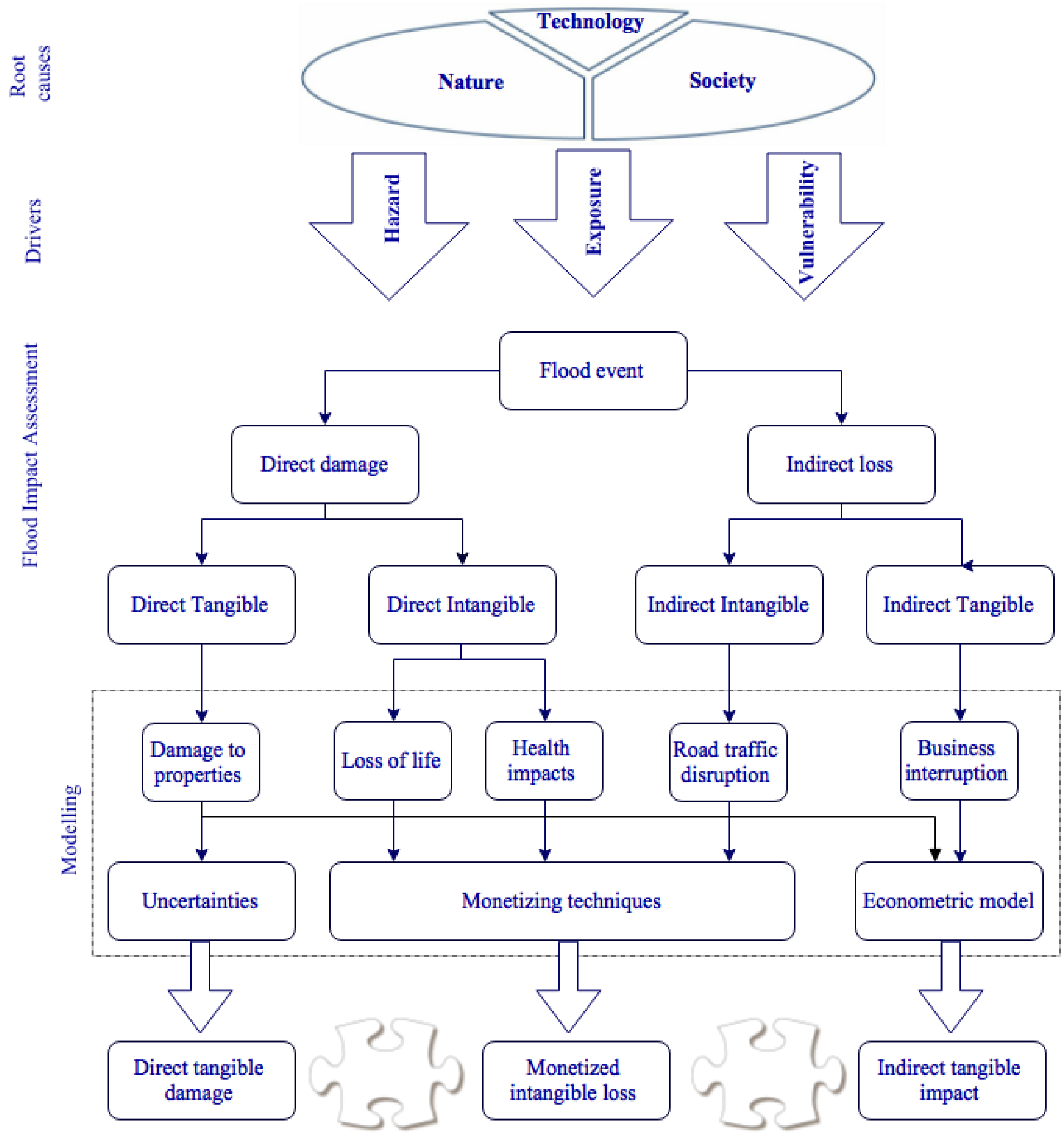

Figure 27: PEARL's framework for impact assessment (from deliverable 3.2.7).

In order to develop a comprehensive flood risk assessment, social and economic impacts will be estimated in the RESCCUE project using different approaches looking at tangible and intangible damages. Within the CORFU project flood risk was assessed for three different categories (pedestrians, vehicles and goods). Specifically, flood risk maps related to current and future scenarios were obtained by combining hazard maps elaborated for return periods of 1, 10 and 100 years and vulnerability maps (Velasco *et al*. 2016).

5.1 Tangible Damage

In the case of direct tangible damages, economic risk can be expressed in terms of monetary values by utilising depths damage curves. For the impacts relating to human or social risk, risk maps can be created multiplying the vulnerability index (i.e. 1, 2 or 3, corresponding to low, moderate and high vulnerability) by the hazard index (i.e. 1, 2 or 3, corresponding to low, moderate and high hazard). In this case, the final risk category scores could vary from 1 to 9 where higher levels indicate higher risk (Figure 28).

Risk Matrix				
		Hazard		
		1	2	3
Vulnerability	1	1	2	3
	2	2	4	6
	3	3	6	9

Figure 28: Risk matrix obtained by multiplying hazard and vulnerability indexes.

5.1.1 Fragility Curves

Fragility curves, unlike damage curves provide an indication as to how an infrastructure or service can withstand an impact causing event before it is impacted and fails. Figure 29 gives an overview of how a fragility curve can be used to assess the resilience of a service or infrastructure against a weather event variable. As an example, consider the fragility curve in this instance relates to a substation and the weather profile represents a rainfall event increasing rainfall intensity that is leading to flooding. As the intensity of the rainfall increases the water depth surrounding the substation increases and critical components (as highlighted earlier in Figure 8) become at risk of failure due to water damage. If flood modelling data reveals that the location of the substation is such that it is susceptible to flooding from relatively low intensity events e.g. 1 in 10yr return period then some flood mitigation strategy and/or additional component protection may be required. These changes would result in a change of the fragility curve thereby protecting the substation against a greater range of rainfall intensities.

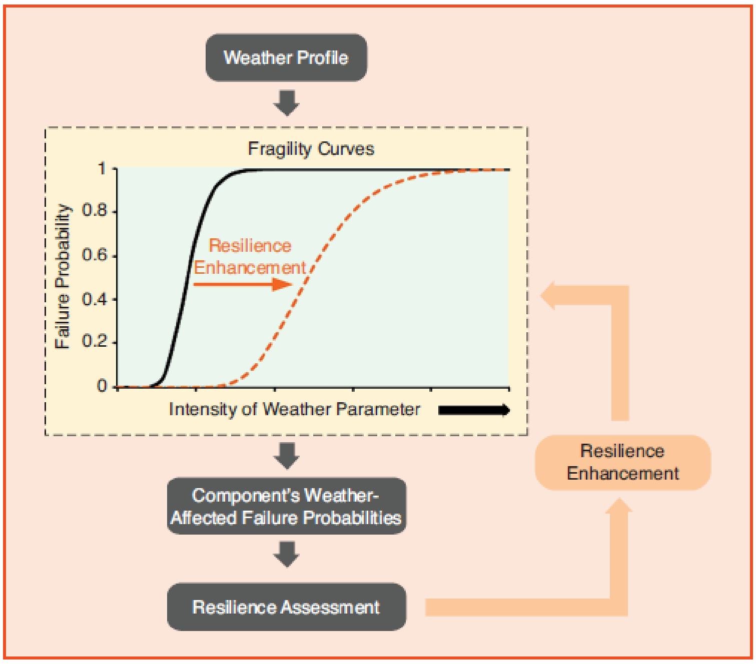

Figure 29: Evaluating and enhancing resilience to weather events using fragility curves (Panteli and Mancarella 2015)

5.1.2 Damage Curves

Economic impacts can be assessed considering only direct flood damages at micro-scale level. In the framework of the EU CORFU project, flood depth maps (hazards maps) in each block of the buildings of Raval District were elaborated and crossed with vulnerability maps (including land use and the related stage-damage curves (Figure 30) (Velasco *et al.,* 2016a) in order to achieve flood damages maps (Figure 31) for different synthetic storms with several return periods for current and future scenarios where different adaptation measures were proposed (Velasco *et al*. 2016).

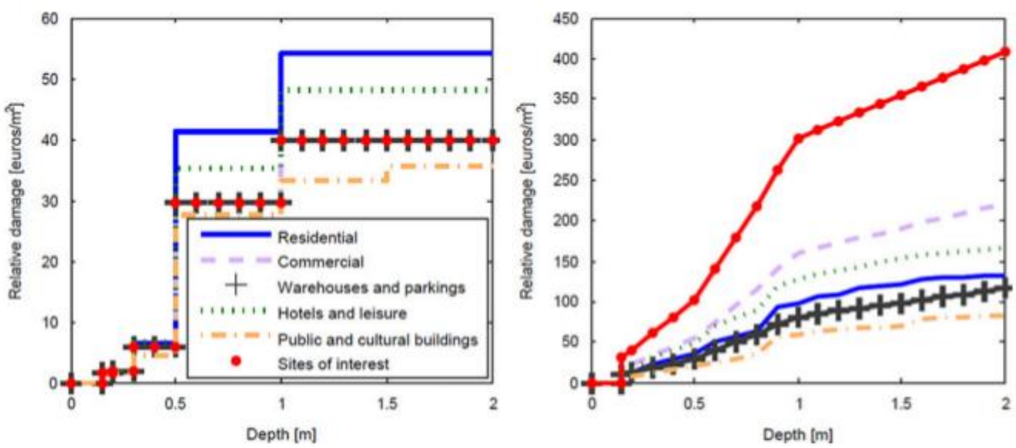

Figure 30. Depth damage curves for the buildings (left) and contents (right) taking into account the local conditions of the Raval district taken from Velasco *et al.* (2016).

Figure 31: Flood damage maps related to the current scenarios in the Raval District for synthetic rainfall events with a return period of year (left), 10 years (centre) and 100 years (right).

Via cross referencing the recorded flood depths against the location and type of property exposed to flooding and its related depth damage curve it is possible to estimate a monetary value of damage. One proposed methodology used by Bristol City Council (2015) in the quantification of damage was to consider not only the depth of the water but also the wetted perimeter of the building (Figure 32). Here, due to the "staircase" effect of flood data outputs, the wetted perimeter is in fact based on a 2 m buffer zone around the building (the buffer zone has to be greater than that of the grid cell resolution from the flood model output). The parameters used therefore in this instance to determine whether a building has been flooded were:

- Buffer distance: 2m
- Minimum proportion of wetted perimeter: 0.5 (50%)
- Minimum flood depth: 200 mm

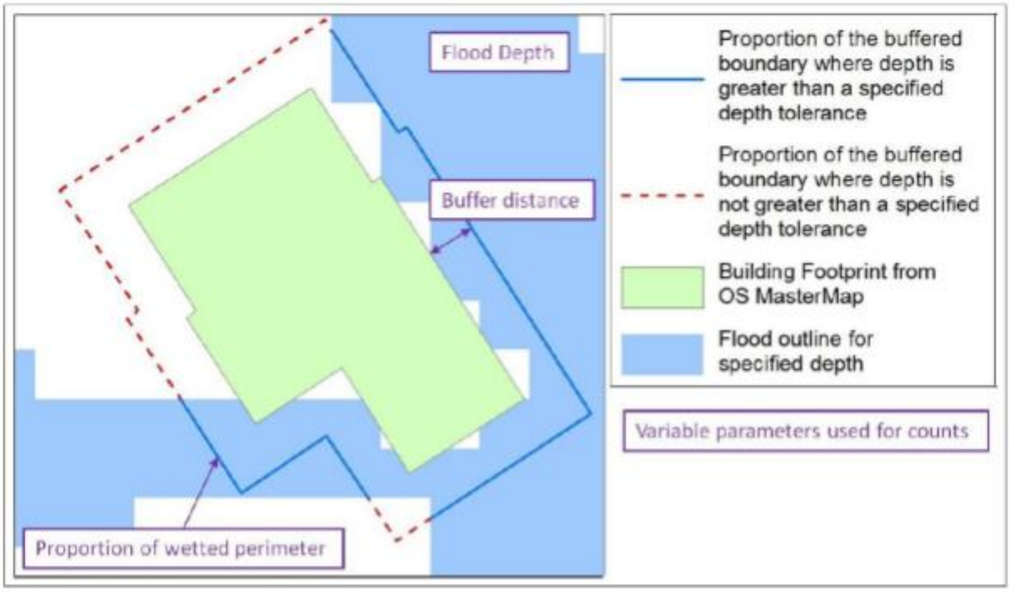

Figure 32: Variable parameters used in flooded building count (Bristol City Council 2015)

On the other hand, in the cities there is a great diversity of vehicles, being the cars that more predominate. During a flood event these can be dragged, overturned or can even float and move with the flow of water. The instability of vehicles has been studied by different authors (Martínez-Gomariz *et al*. 2016). However, vehicles, even if they do not reach the stability limit, will receive the impact of the flood, resulting in economic costs that cannot be neglected. In this sense, damage curves associated with cars can be presented, with the same criteria as for buildings, in order to find the damages to the vehicle as a function of the water depth. This approach is found in the literature although it is a less mature research than damage curves for buildings and has been carried out by a small number of authors. Some US entities such as the National Auto Auction Association (NAAA) conduct studies to detect when a vehicle being offered for sale was actually damaged by a flood.

In this section, the different depth damage curves for vehicles that have been found in the literature are presented. The approaches that are summarized in the following table are those proposed in the HAZUS-MH model developed by the US Federal Emergency Management Agency (2015), the criteria proposed in the CRUE project (Francés et al. 2008) and ,finally, the one proposed by the Corps of Engineers of the United States (USACE) (2009) (Table 8).

Table 8. Summary of the depth damages curves identified in the state of the art review. Source: Martínez-Gomariz (2016)

Ref.	Model	Country	Development	Damage	Types of vehicles	Initial Cost	Analysis Approach
(FEMA, 2015; Scawthorn *et al.*, 2006)	HAZUS-MH (FEMA)	EEUU	Synthetic	Relative (%)	Car Light Truck Heavy Truck	New or used applying 50% of new one price	Individual Objects
(Francés et al. 2008)	CRUE	Spain	Synthetic	Absolute (€)	Gasoline Diesel Averaged	No specified	Individual objects every 100 m^2 affected

Ref.	Model	Country	Development	Damage	Types of vehicles	Initial Cost	Analysis Approach
(USACE, 2009)	USACE	EEUU	Empirical-Synthetic	Relative (%)	Sedan Pickup Truck SUV Sports Car Mini Van	Market value	Individual Objects

However, the level of completeness and accuracy are quite different between them. In this sense, the methodology that is found more appropriate is the proposed by the USACE.

The US Army Corps of Engineers (USACE) conducted a study for the development of damage curves for vehicles exposed to flooding. This study is reported as Memorandum: Economic Guidance Memorandum, 09-04, Generic Depth-Damage Relationships for Vehicles (U.S. Army Corps of Engineers 2009). The USACE's Water Resources Institute's "Flood Damage Data Collection Program" collects information from past floods in order to produce reliable estimations on economic damages due to flood events. As part of the surveys carried out to determine the effects of flooding on residential properties, data were also collected on the damage caused to vehicles parked in such dwellings for the ten communities that suffered the greatest floods. The baseline information for the development of such curves was therefore the data provided by the affected owners in relation to the estimation of the vehicle, the damage suffered and the depth of water that affected the vehicle.

Damage curves were developed for five vehicle types from a sample of 640 vehicles. Such data were processed statistically to construct such curves by regression analysis (Table 9).

Table 9. Percentage of damage related to water depth per each vehicle type. Source: Martínez-Gomariz (2016) adapted from USACE (2009)

Sedan		Pickup Truck		SUV		Sports Car		Mini Van	
									
Depth (feet)	**Damage (%)**	**Depth (feet)**	**Damage (%)**	**Depth (feet)**	**Damage (%)**	**Depth (feet)**	**Damage (%)**	**Depth (feet)**	**Damage (%)**
0	0	0	0	0	0	0	0	0	0
0.5	7.6	0.5	5.2	0.5	0	0.5	1.4	0.5	0
1	28	1	20.3	1	13.8	1	29.2	1	17.8
2	46.2	2	34.4	2	30.6	2	52.8	2	38.3
3	62.2	3	47.5	3	45.8	3	72.2	3	56.8
4	76	4	59.6	4	59.4	4	87.4	4	73.3
5	87.6	5	70.7	5	71.4	5	98.4	5	87.8
6	97	6	80.8	6	81.8	6	100	6	100
7	100	7	89.9	7	90.6	7	100	7	100
8	100	8	98	8	97.8	8	100	8	100
9	100	9	100	9	100	9	100	9	100
10	100	10	100	10	100	10	100	10	100

Ultimately, the purpose of the memorandum is to provide guidelines for the generic use of damage curves developed for flood risk management studies requested by the USACE; who argue that not all studies require a damage curve for vehicles, as they can be considered as housing contents as well. These curves (Figure 33) will be normally used in studies for urban flooding since in rural areas the density of vehicles is not considerable.

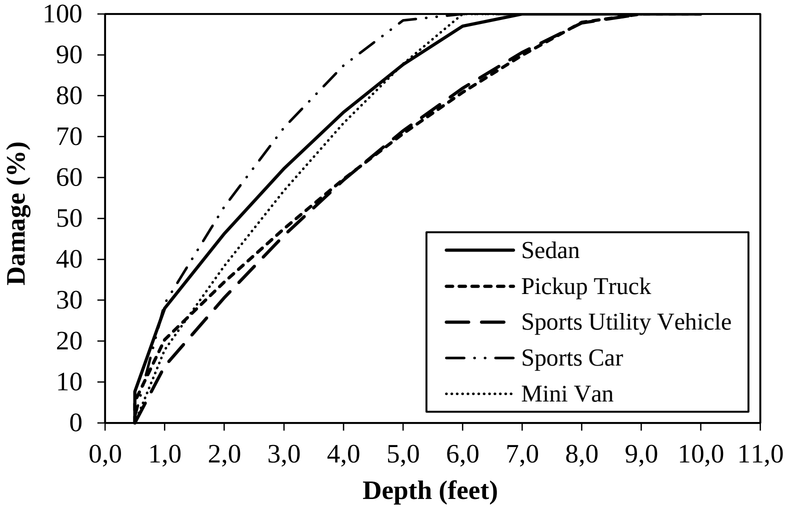

Figure 33. Depth damage curves per vehicle type. Source: USACE 2009

There are two methods to apply these curves, the first focuses on vehicles parked in residential locations and the other focuses on non-residential locations. The first requires different data: the height of the vehicle, which is assumed to be the rise of the affected residential property; An average of vehicles per property in the study area; The classification of these in the different types proposed; And finally, the percentage of vehicles that will actually be parked on the property when the flood affects that area. The memorandum offers different sources of information in the United States to obtain the data required to conduct the assessment of damage to vehicles.

The application to vehicles that are parked in other non-residential locations is analogous but more specific data should be collected. In this case, sources are not provided in the memorandum. Obtaining the number of vehicles parked in shops cannot be carried out using the proposed residential method. The distribution of vehicle numbers and typology should be grouped by individual shop to accurately assess damage. However, the same generic damage curves can be used for both parked vehicles in residential areas and commercial areas.

From the stormwater and wastewater management side, the overall aim in RESCCUE is to improve the accuracy of flood models by allowing for more complex routings along the surface and interactions between the surface and drainage systems. The improved representation of surface flows along with reduced computational time will allow for larger numbers of scenarios to be considered that will allow for greater understanding of the flood risks within the city. These potential improvements will help quantifying the impacts of possible flood event scenarios on infrastructures and services. Other important RESCCUE objectives in this field are the consideration of tangible indirect flood and the improvement of cost benefit analysis regarding the implementation of adaptation measures in order to allow their prioritization on the basis of multi-criteria analysis.

Previous work by Chen et al. (2016) developed an approach and a set of GIS based tools for the estimation/quantification of monetary damage from a range of flood model outputs based on depth damage curves than can be used for future damage assessment analyses. As these tools can facilitate the analysis of impacts from various model outputs it is envisioned that they will serve as basis for comparing/evaluating various methodologies use across each of the cities being analysed.

5.2 Intangible damages

Intangible damages are inherently more complicated to quantify as they're not expressed directly in monetary values, though their effects are still experienced as a result/consequence of an impact. Intangible losses are primarily referenced within two catagories: Social and Environmental (Dassanayake et al. 2010). Social losses are considered to be those that impact human lives and are experienced on an individual basis. Environmental are those where damage has occurred to ecosystems.

Within the framework of CORFU project and regarding intangible damages, risk assessments for pedestrian and vehicular circulation were developed. Specific flood hazard criteria were proposed for hazard assessment regarding pedestrian (Russo *et al*., 2013) and vehicular circulation (Shand *et al*., 2011), while the vulnerability assessment for the two risk categories took into account several social indicators (population density, density of people with critical age, presence of sensitive buildings, etc.) and traffic parameters (daily average traffic intensity) respectively (Velasco *et al*., 2016b). Examples of hazard and vulnerability maps are shown in the Figure 34 and Figure 35, while risk maps (shown in the Figure 36) were obtained crossing these maps according to the risk matrix.

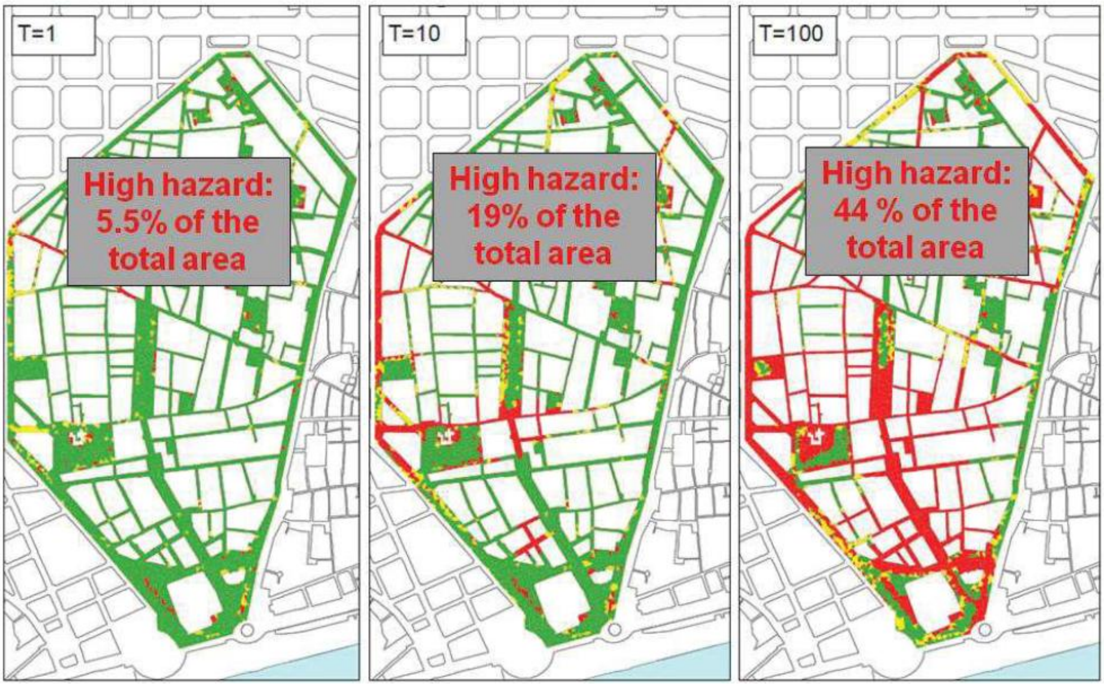

Figure 34: Pedestrian hazard maps of the Raval District for the current scenario. In red high hazard conditions are shown, while in yellow and green colours moderate and low hazard conditions are represented.

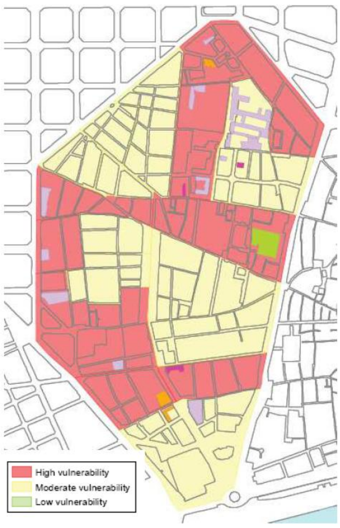

Figure 35: Human vulnerability for the current scenario.

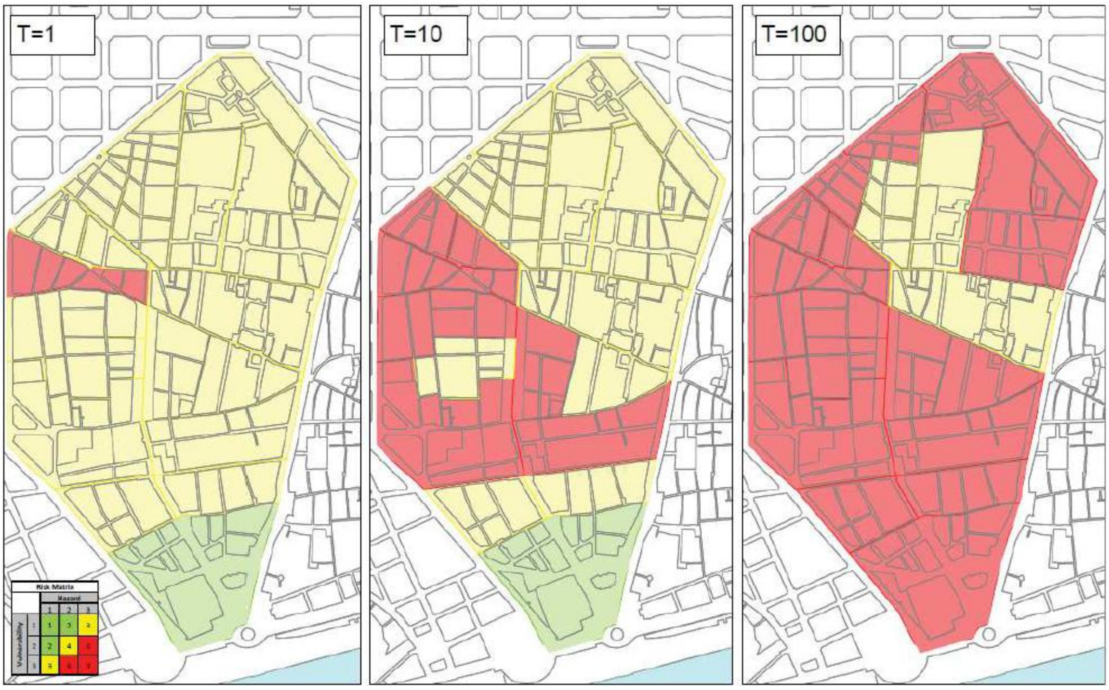

Figure 36: Risk maps for the current scenario related to pedestrian circulation.

The difficulties associated with intangible damages are (as outlined earlier), in the quantification of such impacts. The work outlined in Figure 35 & Figure 36 can be interpreted as a means of risks to human life and also as an inconvenience factor whereby driving speeds need to be reduced or alternative routes to destinations sought during or after a flood event. With regards to risks posed to human life there has been significant work on the "Life Safety Model" (LSM). This model is a 2-Dimensional agent based model that facilitates the production of evacuation plans during disasters (Frongia *et al*. 2016). A paper by Lumbroso and Tagg (2011) looked at a couple of scenarios using the LSM and one of which analysing tsunami risk to the District of Ucluelet in Canada and the benefits of defining multiple safe havens in the event of a crisis. Figure 37 shows a comparative analysis of evacuation distance needed to be covered to reach designated safe havens. In situations whereby mass movement of people and time required to reach safety zone is a crucial factor adequate planning and understanding of the modelling and planning of city responses to disasters is crucial for limiting the loss of life.

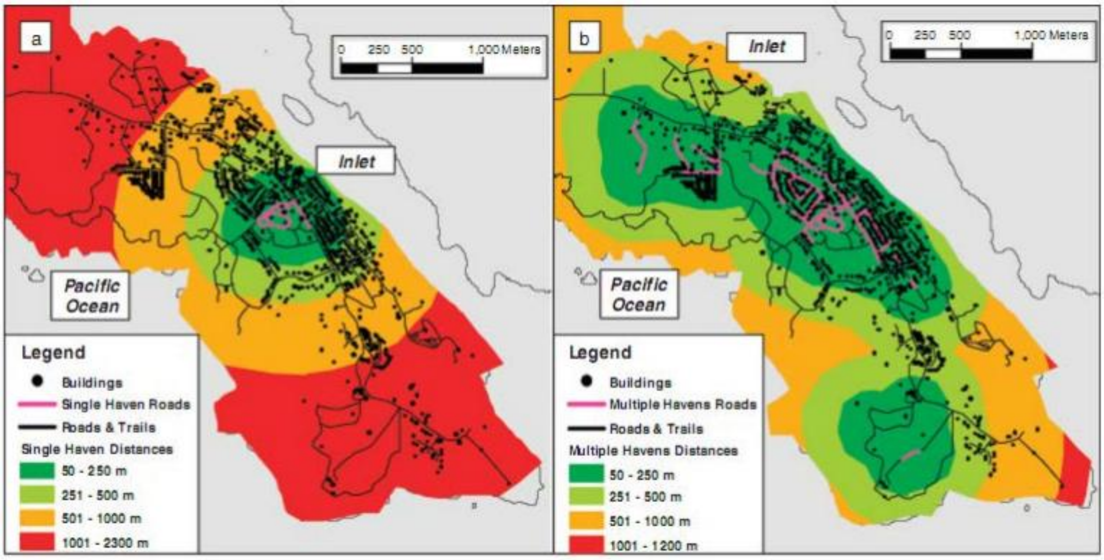

Figure 37: Evacuation analyses: (a) single haven evacuation distances, (b) multiple havens evacuation (Lumbroso & Tagg 2011)

5.3 Linking models

The analysis of certain impact events could be achieved via the use of loosely coupled models. Figure 38 shows an example whereby inputs into Hazard Model$_1$ can be used to generate outputs that could be fed into a subsequent Hazard Model.

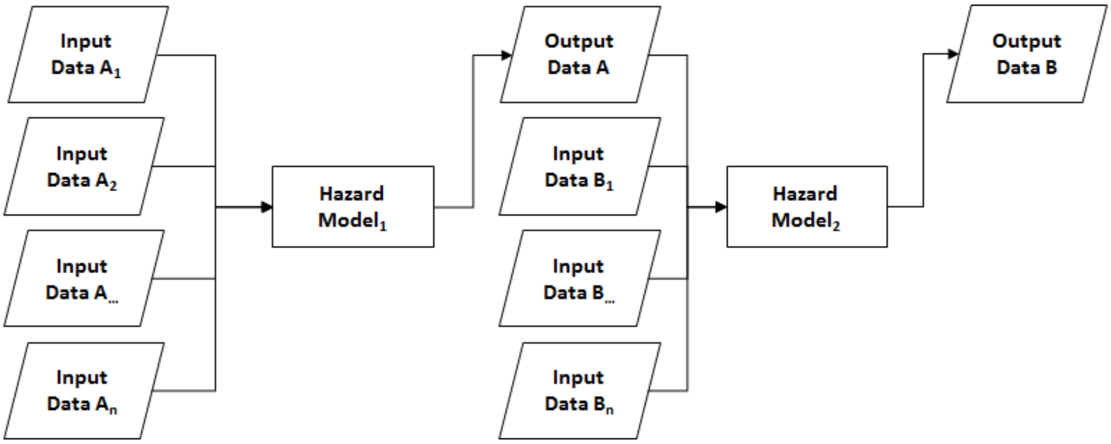

Figure 38. Loosely coupled Hazard model example.

As an example, earlier it was highlighted that the water distribution network is at risk due to seasonal variations of temperature and that these risks are expected to increase as a result of climate change. The impact of temperature on the water distribution network can result in cascading effects on other services. Figure 39 shows that a pipe burst scenario could lead to flooding that can lead to energy grid failure and traffic disruption. The dashed arrow in Figure

39 (linking failure of energy grid to the SUMO Traffic Simulation mode) relates to potential disruptions to traffic flow as a result of power loss to traffic signals and control systems.

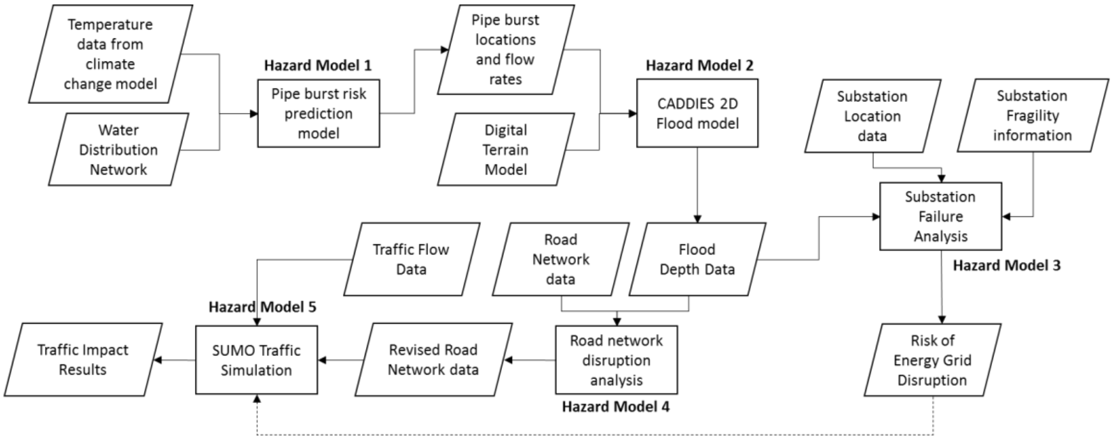

Figure 39: Loosely coupled model example highlighting potential cascading effects.

It is important to note that Figure 39 is merely a snapshot of some of the links between different models the overall linked model approach would be far more complex and affect each of the services and sub-services within the city.

5.4 Commonalities between approaches

The approaches examined for the quantification of both tangible and intangible damages have been derived, in part, via the generation of hazard maps and quantifying the impacts in either monetary terms or in level of disruption. The proposal being considered when building the "big picture" of the city would therefore be to utilise loosely coupled models (as defined in Figure 38Figure 39) to capture possible cascading effects.

6 Summary of analysis

There has been significant research in translating the effects and impacts of hazards on individual services and infrastructures where the majority of which covered hazard based spatial interpretations of the cities vulnerability to climate based events. This document has highlighted that singular hazards can affect multiple services both directly and indirectly and lead to both tangible and intangible damages. The challenges ahead within RESCCUE will be to define the dependencies between services and how given impacts will cascade across multiple services and infrastructures.

7 Appendix

The partners involved within the RESCCUE project have been involved in numerous flooding flood risk, and water cycle related projects over the years such as CORFU[14] , EU-CIRCLE[15] , PEARL[16] , PREPARED[17], Safe & SuRe[18] and BINGO[19].

7.1 CORFU

The CORFU (Collaborative research on flood resilience in urban areas, www.corfu7.eu) project was created with the aim of enabling European and Asian partners to learn from each other through joint investigation, development, implementation and dissemination of short to medium term strategies that will enable more scientifically sound management of the consequences of urban flooding in the future.

7.2 EU-Circle

The EU-Circle (http://www.eu-circle.eu) project's scope was to derive an innovative framework for supporting the interconnected European Infrastructures resilience to climate pressures, supported by an end-to-end modelling environment where new analyses can be added anywhere along the analysis workflow and multiple scientific disciplines can work together to understand interdependencies, validate results, and present findings in a unified manner providing an efficient Best of Breeds solution of integrating into a holistic resilience model existing modelling tools and data in a standardised fashion.

7.3 PEARL

The PEARL (Preparing for Extreme And Rare events in coastal regions, http://www.pearl-fp7.eu) project aims at developing adaptive risk management strategies for coastal communities focusing on extreme hydro-meteorological events, with a multidisciplinary approach integrating social, environmental and technical research and innovation. PEARL will consider all fundamentals in the risk governance cycle, focusing on the enhancement of forecasting, prediction and early warning capabilities and the building of resilience and reduction of risk through learning from experience and the avoidance of past mistakes.

7.4 PREPARED

The PREPARED project (http://www.prepared-fp7.eu) was setup to demonstrate the technological preparedness of water supply and sanitation systems of ten cities in Europe to adapt to the expected impacts of climate change. It showed how the water supply and sanitation systems of cities and their catchments can adapt and be resilient to the challenges

[14] http://www.corfu7.eu/
[15] http://www.eu-circle.eu/
[16] http://www.pearl-fp7.eu/
[17] http://www.prepared-fp7.eu/
[18] http://emps.exeter.ac.uk/engineering/research/safesure/details/
[19] www.projectbingo.eu/

of climate change; and that the technological, managerial and policy adaptation of these PREPARED cities can be cost effective, carbon efficient and exportable to other urban areas within Europe and the rest of the world. In addition to this the PREPARED project looked at early warning systems, as well as short- and long-term response strategies for urban areas.

7.5 Safe & SuRe

The goal of Safe & SuRe (http://emps.exeter.ac.uk/engineering/research/safesure) is to develop a new paradigm in urban water resource management as a means to respond to emerging challenges and an uncertain future.

7.6 BINGO

Project BINGO (Bringing INnovation to onGOing water management) is a Horizon 2020 European Funded project that aims at providing practical knowledge and tools to end users, water managers, decision and policy makers affected by climate change to enable them to better cope with all climate projections, including droughts and floods (http://www.projectbingo.eu/).

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