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.

Development of methodologies for modelling of cascading effects and translating them into sectorial hazards

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Date: 20 JUNE 2018

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

DELIVERABLE NUMBER:	3.3
DELIVERABLE NAME:	Development of methodology for modelling of cascading effects and translating them into sectorial hazards
WP:	WP3
DELIVERY DUE DATE:	30/06/2018
ACTUAL DATE OF SUBMISSION:	18/10/2018
DISSEMINATION LEVEL:	Public
LEAD BENEFICIARY:	UNEXE
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Document history

DATE	VERSION	AUTHOR	COMMENTS
20/03/2018	1	B. Evans	Skeletal template

16/04/2018	2	B. Evans & IREC	Information provided by IREC for energy sector
24/04/2018	3	B. Russo	Review of the first draft document
08/05/2018	4	B. Evans & Cetaqua	Contributions to the Waste sector from Eduardo
25/05/2018	5	B. Evans & BCC	Contributions to Bristol section
30/05/2018	6	Opticits & EIVP	Contributions to Section "Holistic approach to analyse cascading effects using HAZUR
31/05/2018	7	LNEC, AdTA, EDP, CML	Contributions to sections about Lisbon City and their Traffic modelling approach
01/06/2018	8	Barcelona City Council	Contributions from Barcelona City council about cascading failures within their city
15/06/2018	9	Wessex Water	Contribution provided in relation to the Waste Water Ssction
18/06/2018	10	LNEC and CML	Updated contributions in relation to Lisbon
19/06/2018	11	Wessex Water	Further contributions provided in relation to Waste Water section
25/09/2018	12	AQUATEC	Final internal review
12/10/2018	13	B. Evans & B. Russo	Changes made based on Internal review
16/10/2018	13	B. Evans & N. Duarte	Minor amendments to figures for EDP section

1. Changes with respect to the DoA
   None

2. Dissemination and uptake
   Public

3. Short Summary of results (<250 words)

Deliverable 3.3 – "Development of methodology for modelling of cascading effects and translating them into sectorial hazards" is following on from D3.2 "Tools with updated impact assessment models" whereby it seeks to investigate what constitutes cascading effects within each of the case study areas and how to quantify impacts from climate driven hazards. This document highlights the interdependencies of each of the critical services identified previously within D3.2, summarises the impact assessment models that can be applied and the cascading effects that either cause the failure or reduction of a service in the analysed services.

4. Evidence of accomplishment

This report provides a comprehensive outline of the interdependencies between difference critical services being analysed within the cities and how cascading failures from climate driven hazards on these services can be quantified and potentially mitigated.

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Summary Figures

1 Introduction

The preceding documents D3.1 & 3.2 have shown methodologies that are and will be used in the quantification of impacts within RESCCUE on infrastructures and services. The implications of impacts however are not solely limited to those directly affected infrastructures and services but can, in fact, lead to cascading failures of other infrastructures and services. This document highlights the approaches employed within RESCCUE to represent and analyse impacts on infrastructures responsible in providing services and the cascading effects that can arise from an impact driven events.

As part of Deliverable 2.1, a number of critical services and their interdependencies was identified as highlighted in Table 1. These services are investigated within the scope of this document, as well as how failures of such services can impact upon others.

Table 1 - Identified interdependencies within RESCCUE research sites.

Service	**Service Interdependency**	**Comments (*Service required for…*)**
Energy	Transport	Access to control centres by engineers is required in the event of failure in the systems
	Telecommunications	Real-time monitoring of network
Transport	Energy	Supply of power to traffic management systems along network
	Telecommunications	Real-time monitoring and control of traffic management systems in the city
Waste Disposal	Transport	Removal of waste bins from city
	Energy	Processing of collected waste
Water Treatment and Distribution	Energy	Pumping of water and water treatment work. In the event of failure of pumps access by engineers to back-up generators may be required.
		Sudden loss of power to pump can lead to “water hammer effect” and potentially cause pipe bursts.
	Telecommunications	Monitoring network and pumping control
Urban Drainage	Electricity	Powering systems for pumping and treatment of waste water. In the event of failure of pumps access by engineers to back-up generators may be required.
	Telecommunications	Real-time monitoring of movement sewers devices and treatment of waste water

The hazard modelling aspects of RESCCUE for each of the cities are outlined in detail within Deliverable 2.2. In this deliverable, hazard models that are used as tools for quantifying initial impacts to infrastructures and services have been fully described. Within the scope of this document, examples in relation to the hazard analysis from D2.2 are therefore shown for reference to provide context of the analytical processes involved when determining impacts and subsequent risks of cascading effects.

Cascading effects pose significant issues to cities infrastructures and services and, due to the complexities of models and the way service providers work, they are not always completely understood. Within deliverable D2.1, in the three RESCCUE research sites (Bristol, Barcelona, and Lisbon), some potential cascading failures that could occur and/or are of concern to their respective cities have been identified. As part of this process, they defined the urban services within a city and their critical elements that ensure its functionality that may susceptible to failure in the event of specific impacts. For example, in the case of Lisbon, some of the identified potential service failures that would occur due to a loss of electricity would be water supply, wastewater treatment, transport such as trams and trains, street lighting, telecommunications, and urban drainage (due to loss of pumping and control systems). The historical records in each of the cities (Annex sections 6.1.1 – 6.1.3) have highlighted the complexities of the chain of cascading failures that can occur from climate driven events. An example of such complexities is depicted in Figure 1. The proceeding sections look at the critical services within the cities, the consequences of failures, mitigation measures and strategies in place to reduce the impact of cascading failures during climate driven events.

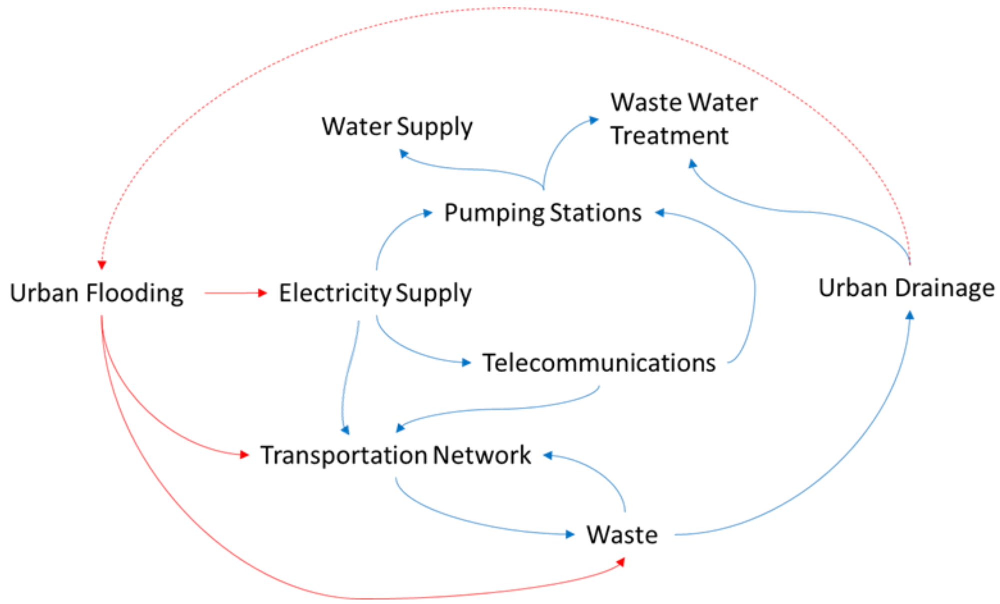

Figure 1 - Example of complex chain of cascading failures from a flood event.

As part of the RESCCUE project, the work herein outlined in this document is focusing upon the interaction/interdependencies between several urban services analysed in the framework of RESCCUE project: Energy, Water Distribution, Urban Drainage, Waste Water Treatment, Waste, Beaches and Transport. This analysis has been carried out considering both detailed and holistic perspectives and how these are used to quantify the impacts and risks of cascading failures as a result of selected hazards.

2 Defining cascading effects in selected critical service sectors

The following sections look at the interdependencies and cascading effects within varying sectors. These consider the means of how impacts from hazards are trigger a failure of a service, the interdependencies between different services, the level of redundancies and measures in place to prevent/delay cascading failure and resulting cascading failures that result when the mitigation measures in place during an impact are overwhelmed.

2.1 Cascading failure risks within the energy sector

The energy sector faces multiple threats from extreme climate events which may disrupt supply, alter demand patterns and/or damage infrastructures. A clear example of this can be found in New York, where Hurricane Sandy caused major blackouts affecting eight million residents in 2012 (PlanNYC, 2013). Identifying and evaluating the possible impacts to help mitigate as much as possible the negative consequences affecting the population is therefore critical to improve the resilience of Critical Infrastructures (Cis) and urban services. Table 2, based on information from Mendiluce (2014), shows how various climate risks can impact power distribution systems.

Table 2 – Climate risks and electrical impacts on a distribution power system

Climate risk	Electrical impact
Heavy rain and thunders storms	- Vegetation growth affecting lines can cause fires - Corrosion of components submerged in water
Heavy snowfall	- Collapse of pylons - Cable breakages
Ice	- Flashovers on transformers and their consequent tripping
High temperatures	- Drooping of lines can cause fires
Flood	- Damage in substations and lines - Electrical tower foundations are risked
Storms (including strong winds)	- Collision of lines often produces fires - Towers and poles can collapse

In a cascading process within an interconnected system such as a meshed urban power grid, the failure of one component within the grid can trigger the failure of other components. For instance, if an underground line trips, all the components which uniquely depend on such line will be offline but, at the same time, some other grid components which are not linked to this line might start operating out of their limits (e.g. a line out of thermal limits or a bus voltage above the limit imposed). Furthermore the failure of power distribution may have further cascading consequences upon other services and CI's that are dependent upon that power. Component failure therefore can result in internal cascading failures within the power distribution system and external cascading failures on infrastructures and services dependent upon the power distribution.

In the event of any power disruption, the main objectives are therefore to minimize the load unsupplied to consumers whilst prioritizing minimum disruption to key CI's and services such as, for example, hospitals.

2.1.1 Assessing cascading failures and effects in the Energy Sector

The assessment of the impacts and cascading effects both directly within the energy sector (through interconnected components), and outside the energy sector that require the supply of power to function, needs to be analysed spatially to define where the interdependencies between components in the grid and infrastructures are defined along with defining what mitigation strategies are place. As part of Task 2.2 hazard assessments for a number of flood events for different return periods including river flooding, sea flooding and historical heavy rainfall events (as shown in Figure 2) have been carried out. The impacts of these hazards can be assessed both spatially and temporally relative to the electrical infrastructures present within each of the case study areas. An impact assessment based on a "Physical Modelling" approach (as outlined later in Section 4) can then be carried out to assess the level of disruption a given hazard has on the supply of power and the potential cascading failures.

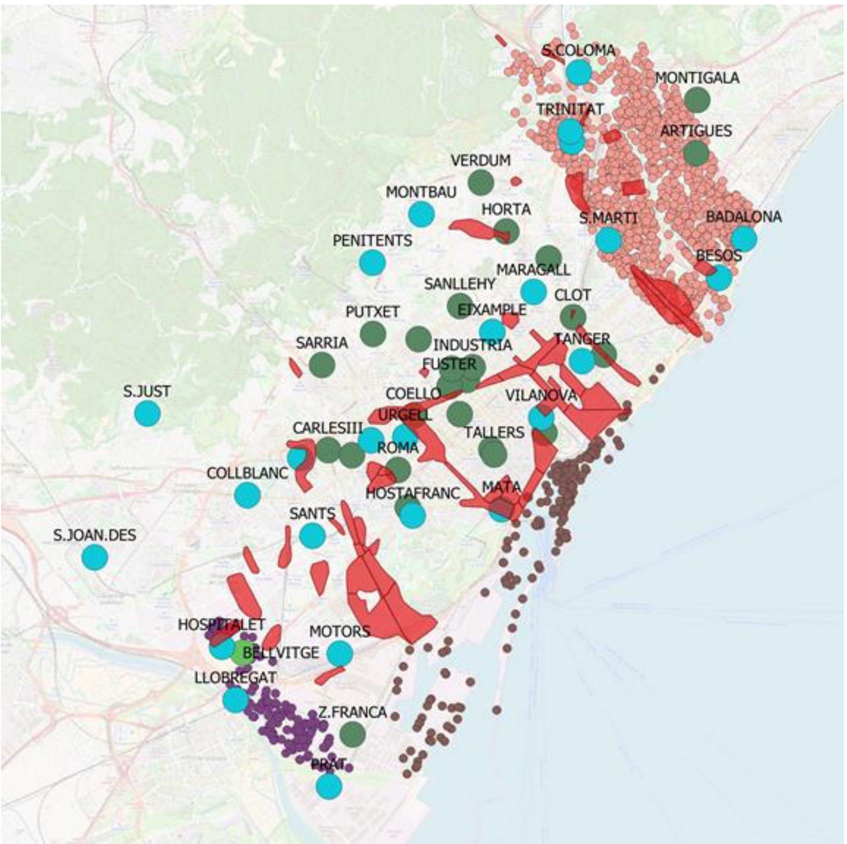

Figure 2 – Potential impacts zones (red) relative to electrical infrastructure components within Barcelona area.

Where data available the cascading disruption/failure caused to components within the power distribution network that result due to a failure elsewhere in the network can be defined via analysing defined dependencies within the network. Figure 3 shows the connection between some of the components (those of interest) within the network in Barcelona where circles with the letter “S” inside depict substations and the smaller circles represent distribution centres. By knowing these connections, the cascading effects due to failure of one component within the grid on other components downstream (or upstream depending on re-routing methods being used) can be assessed. By analysing the potential failures of components both in location and duration the energy sector can determine which other components in the system are now under and have the potential of failure. If these components were to fail this could then propagate further through the network. Further to this information relating to what infrastructures (both CI and non-CI) the substations and distribution centres supply power can also be included and assessed when analysing impacts and resulting cascading effects where such information is available. In situations whereby this data is not present, alternative methods may be used as approximations as defined later in section 3.1.2. This initial information relating to the power distribution network provides valuable insight in relation to impacts and cascading failures within the grid. These failures, however, may not necessarily lead to the failure of CI’s due to contingencies in place that allow for the re-routing of power where possible and/or back-up systems to continue the supply of power to vital components until the network is fully restored.

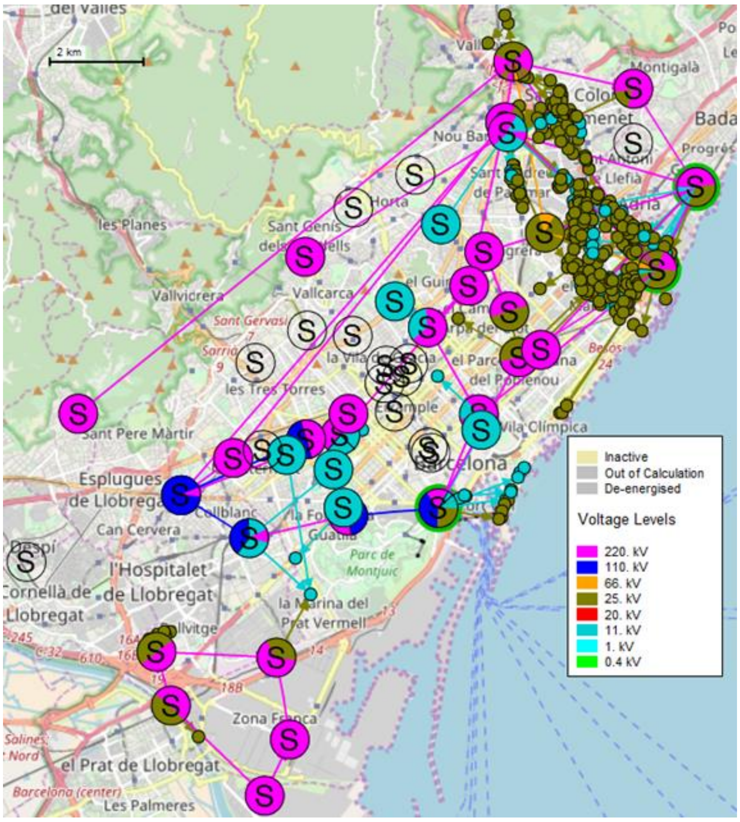

Figure 3 - High-level view of Barcelona's power system modelling

2.1.2 Contingencies/redundancies employed to minimise impacts and cascading effects in the energy sector

Automatic reconfiguration of energy distribution systems is a key factor in responding quickly to emergency situations and allows continuous online-assessments to initiate the corresponding responsive actions. Assuming the power system has great observability of measurements to allow for the detection and localisation of faults, a self-healing strategy within two stages is outlined. As an example, the Distribution Planning System (Dplan) is being implemented within the city of Lisbon (highlighted in detail within Deliverable 2.2) and it can simulate impacts from possible climate scenarios and suggest and implement redundancies/re-routing of network in the event of a failure.

A self-healing algorithm can determine the new configuration of the power system through the reconnection of lines and clusterisation of the power system, and the performance indices can be applied to analyse the new system configuration. The first stage of the algorithm is the black-start capability, which consists of setting the energising sequence of those generators in the power system that have the ability to generate power without the need of external inputs e.g. storage system. Afterwards, in the second stage of the algorithm and once all the electric components have been reenergized, load restoration takes place. On this second and final stage, the objective is to minimize the load unsupplied through the reconnection of lines and optimally clusterise the power system into numerous micro-grids to minimize as much as possible the impact on consumers. Figure 4 shows an example of carrying out a self-healing strategy and how the electrical network is clustered into three microgrids (MGs) after a fault event (line between buses 3 and 4) to minimize the impact on the affected customers. Thus, each MG can operate autonomously supplying several loads. The MG has generating units such as: energy storage (ES), photovoltaic (PV) and wind turbines (WT). Eventually, the formation of clusters is a solution which allows the operation in islanded mode in case there is no possibility to reconnect to neighbor electrical assets as these might also be affected by the fault. Moreover, clusterisation would allow to decentralize self-healing decisions through the management of local communications instead of one central communication unit.

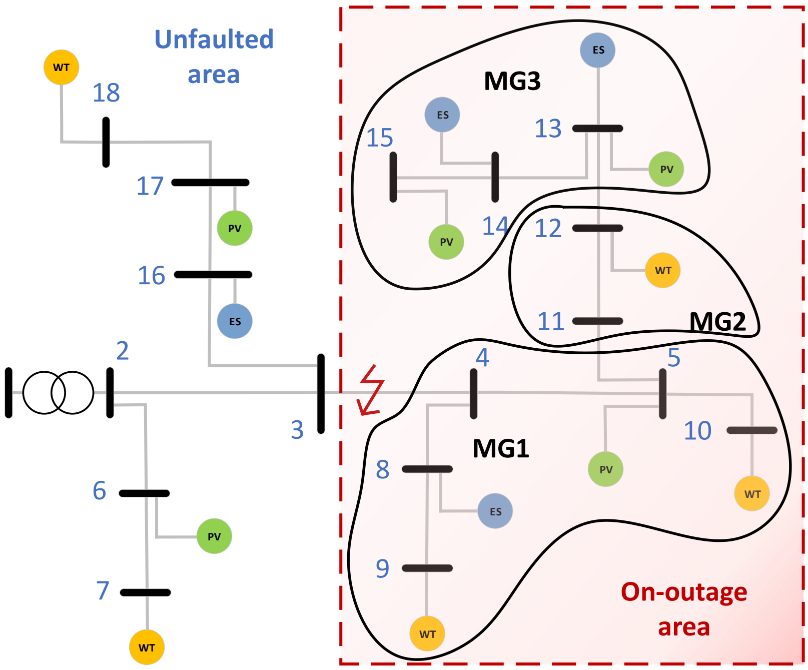

Figure 4. On-outage area sectionalized in three MGs after a fault event by applying a self-healing strategy

The methods being investigated aim to carry out two kinds of self-healing strategies with different time perspectives: planning and operation. Self-healing is the automatic reconfiguration of the network after a failure event and it can be applied to smart power systems. Therefore, self-healing will only be possible to apply once the power system of a city has reached a high level of intelligence, especially in terms of communication. For this reason, it is assumed that the system is not only redundant electrically but also in telecommunications i.e. parallel communication infrastructure which functions separately from the main telecommunication services in a city, as these might also be affected by the fault.

Planning: a mathematical optimization problem has been formulated to perform medium and long-term analysis to determine how the electrical system should optimally respond under a certain failure caused by an extreme climatological event which often takes place in the network. This algorithm could be helpful for electric utilities to find out how the optimal operation of the grid should be under specific electrical failures they have identified as critical, without the need of investing on new equipment but simply on adjusting the network topology. Therefore, the design of the future network would be an output of such algorithm. Moreover, forecasting (long-term and short-term) weather and demand profiles has to be considered for these studies. The main objective of this planning strategy based on self-healing relies on minimizing the unsupplied load whilst maintaining all the grid operational constraints. As secondary objectives, switching actions of cutting line switches can also be minimized to extend the lifecycle of such devices. Additionally, the power system can also be optimally sectionalized into several (MGs) which can operate autonomously by providing reliable power from distributed generators (DGs) to the maximum possible number of the affected customers.

Operation: a short-term analysis has been formulated to automatically reconfigure the electrical grid after a certain failure caused by an extreme weather event. Under such emergency situations, this self-healing strategy has the main objective of minimizing load unsupplied to customers in a short interval of time. Several other objectives can be introduced in the optimization algorithm, such as the ones mentioned for the planning studies above. The difference with the planning strategy is that this study is in real-time and therefore the grid must respond quicker to grid contingencies. An application of this strategy could be after an electrical substation has interrupted its service due to flooding and the power system sensors communicate this failure by sending current network state measurements to the optimization algorithm, which will analyze the current condition of the system and provide a new network configuration of the grid based on the received real input data. Such algorithm is meant to run every instant new network input data is gathered to reach the full potential of the network.

2.2 **Cascading failure risks in the Water Distribution Sector in relation to burst pipe scenarios**

Underground drinking water infrastructure is designed to withstand the variability of forces during its lifetime before failures occur. As mentioned in Deliverables 3.1 and 3.2, one of the identified causes of failure of the water distribution system is due to pipe burst events. These events can lead to the loss of water supply and possible flood scenarios, both of which can result in cascading failures of other services that are either dependent upon supply or impacted directly or indirectly as a result of the flood water. Several studies were conducted analysing the influence of local weather conditions on pipe failures with increased pipe failure being observed in winter and summer periods (mainly during periods of freezing and drought). Consequently, temperature and temperature changes, freezing index, days of air frost, soil moisture deficit, antecedent precipitation index and rain deficit were identified as most important weather parameters (Wols & van Thienen, 2016) and climate change may accelerate or decelerate these processes (UKWIR, 2012).

The effects of a burst water pipe can be quite severe resulting in significant visible damage due to the subsequent flooding, cause disruption to services such as transport and energy distribution, or less visible but severe damage over time via underground erosion leading to development of sinkholes.

2.2.1 Assessing cascading failures and effects due to pipe burst events

A very representative event occurred on the 24th November 2016 (Figures Figure **5**Figure 6), in Barcelona where there was a series of cascading effects experienced as a result of a main pipe burst generated by an unknown failure. Specifically, the pipe burst resulted in serious traffic disruption along the high speed rings (with 6 kms of queuing traffic) and a water supply cut during 3 hours approximately affecting one of the main hospital of the city (Vall d'Hebron) and additionally 10,000 inhabitants. The emergency room of the hospital was unable to function and 33 hospitalised patients were affected for 2 hours.

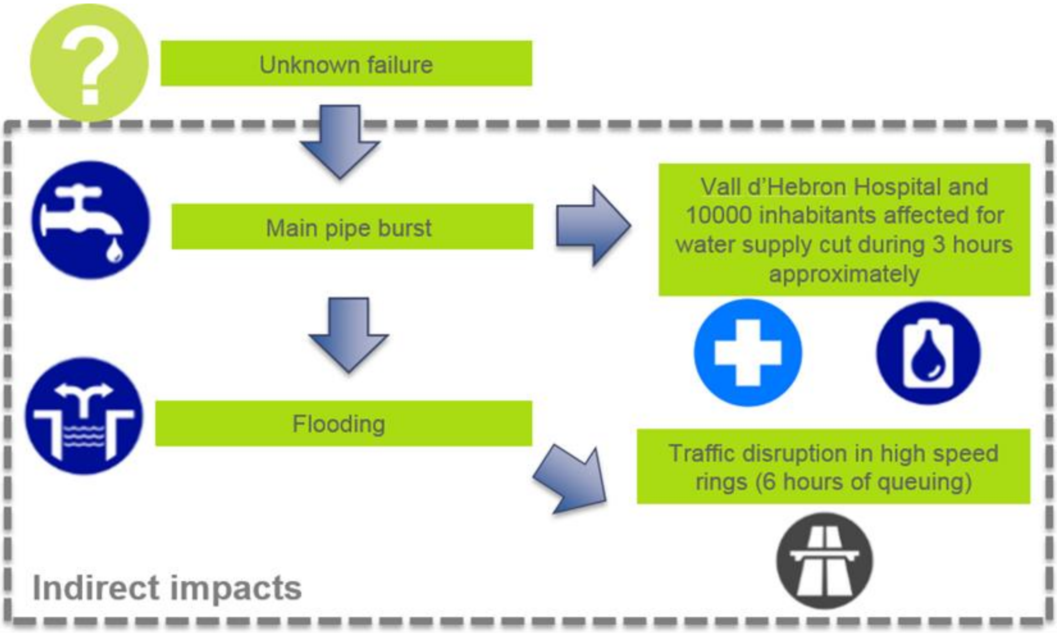

Figure 5 - Cascading effects of a main pipe burst in Barcelona occurred on 24th November 2016.

Figure 6 - Impacts of a main pipe burst in Barcelona (sources: local media).

In the framework of RESCCUE and specifically, in the Task 2.2 of WP2, an integrated sectorial model has been developed in order to identify critical assets affected by potential failures of distribution pipes. The key elements of this model are:

- Digital terrain model
- Topographic and hydraulic information about supply network
- GIS (with spatial analyst module)
- Location and main characteristic of critical infrastructures
- 2D hydraulic model

The objective of this model is the identification of critical infrastructures in flood prone areas produced by pipe burst. A GIS stochastic analysis of potential failures is initially carried out, and target events of failure are selected on the basis of high concentration of critical infrastructures in flooded areas. Once the pipe burst events are selected, a 2D detailed hydraulic model is used to determine the overland flow and the related parameters (flow depths and velocities) in proximity of the critical assets. According to the maximum values of flow parameters and their timing evolution (i.e. flood duration), the propagation of flooding impacts on strategic infrastructures and urban services can be assessed and the likelihood of failure of such services determined. Figure 7 shows the flood extents and depths of a simulated pipe burst at Roger de Flor in Barcelona and the proximity of the flood water to local CIs.

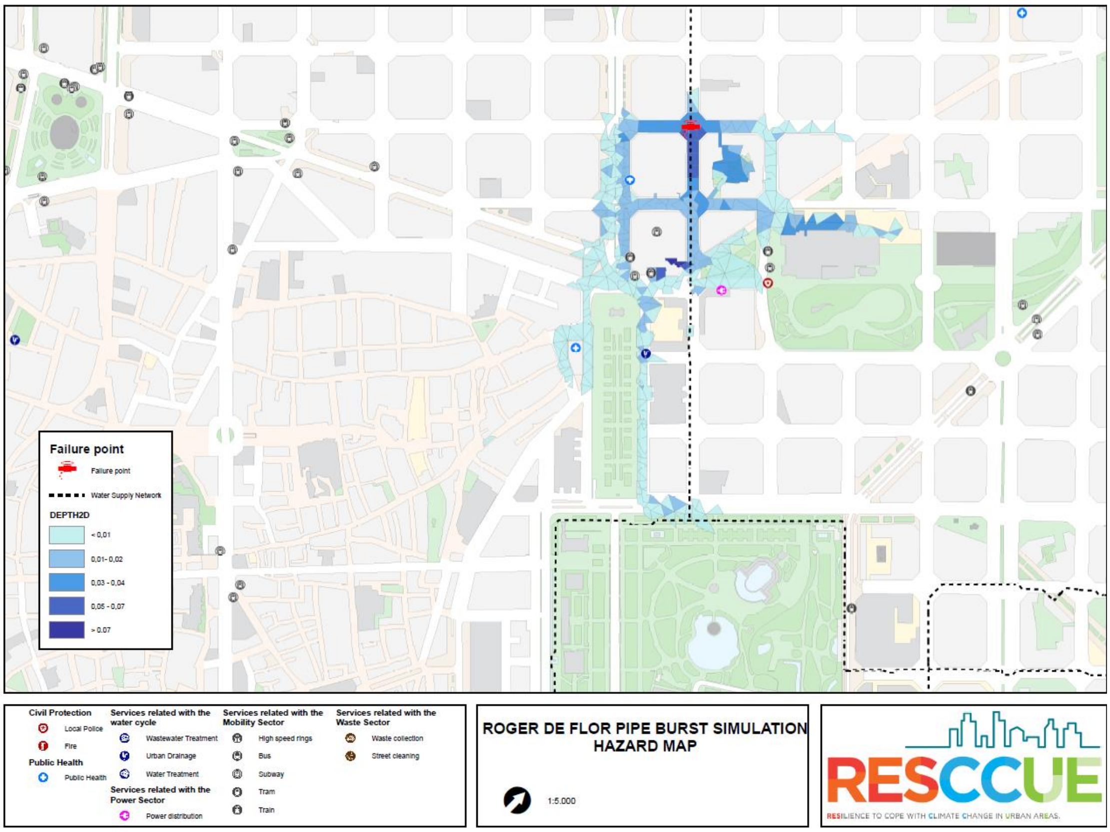

Figure 7 - Hazard map depicting flood extent and depths relative to CIs after Roger de Flor pipe burst simulation.

2.3 Cascading failure risks within the Urban Drainage network during flood scenarios

The impacts of extreme rainfall events and subsequent urban flooding is of significant concern for all of the cities within the RESCCUE project. As part of the analysis of impacts in each of the three research sites, each city is employing the use of 1D/2D Urban Drainage models that are described in detail within Deliverable 2.2.

Under flooding conditions, failure of the drainage network can result in the surcharging sewers that can result in additional surface flooding and also have impacts on the highway and traffic even after the floodwater has receded, as a result of:

- Dislodging/ blowing off of manhole covers, which can be an obvious danger to traffic, pedestrians and emergency services, particularly if the roadway subsequently becomes flooded and the manhole is not visible,

- Damage to the fabric of the highway, caused by the manhole becoming pressurised, lifting the cover slab. Again, a hazard to traffic and vehicular access after the event,

- Damage to the road, footpaths and walls caused by failure and discharge from pressurised pipes, causing washout of pipe bedding, allowing voids to form in surrounding soil and potential surface collapse or sinkhole formation.

- CSO Discharges resulting in contamination of water bodies.

Figure 8 - Examples of damaged surfaces during flooding event in Wuppertal (May 2018).

Flooding in one location can be inadvertently transferred to a downstream part of the sewerage catchment by the action of well-meaning individuals, by lifting inspection covers on their own property in an effort to drain floodwater away – only to fill an already overloaded system and possible cause flooding to nearby and downstream properties.

2.3.1 Assessing cascading failures and effects within the Urban Drainage Sector

Each of the research sites are carrying out detailed analysis of future climate scenarios to identify regions within their respective cities that may be at risk of flooding due to over-capacity of the urban drainage network. For example, Bristol City Council in collaboration with Wessex Water have been working on the Surface Water management Plan (SWMP) to identify areas of highest risk with respect to pluvial flooding using a 1D/2D flood modelling approach. This analyses is being carried through the use of Infoworks ICM software. The 1D modelling component provides insight into how the sewer system responds to rainfall events and can lead to sewer discharge (Figure 9) and these sewer discharges can then be modelled within a 2D surface model to predict the flooding that can occur as a result of this discharge (Figure 10).

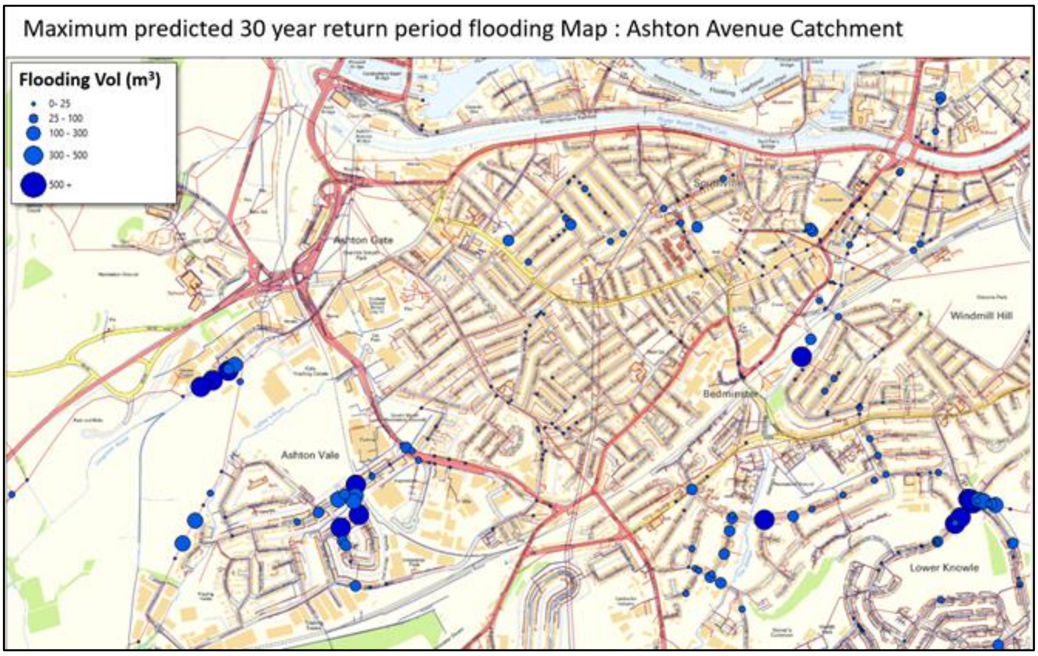

Figure 9 - Sewer discharge prediction based on 30 year return period storm

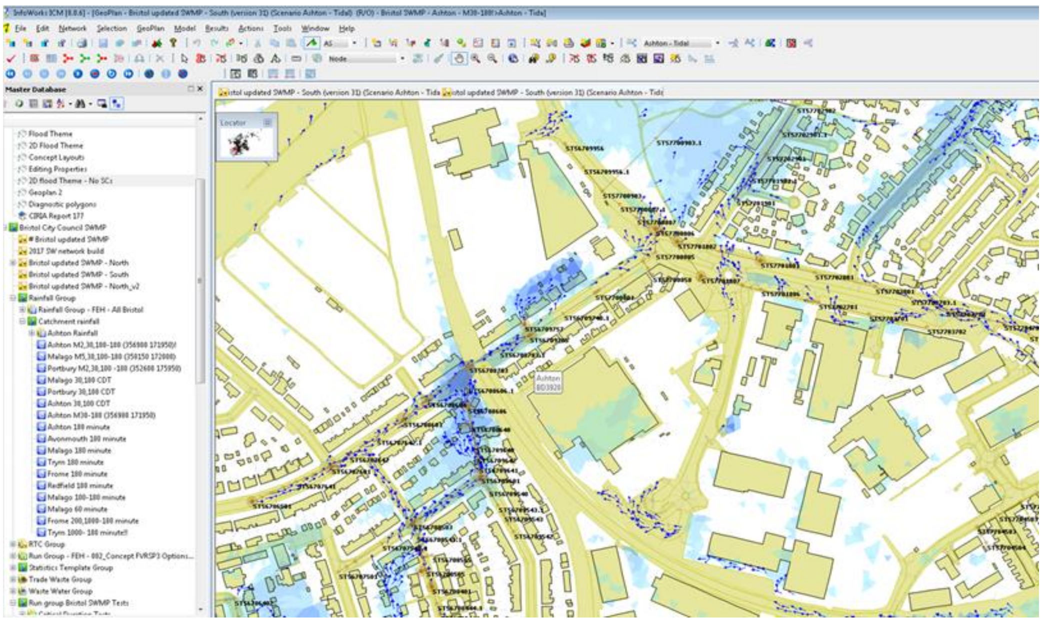

Figure 10 - 2D Surface flood predictions based on sewer discharge event

Storm-induced flooding incidents, by their nature, cover a wide region, therefore prioritisation of response to incidents becomes critical due to the operational resources available to deal with the incidents being finite. Good knowledge of the sewerage network and known "hotspot" priority areas, coupled with availability of additional resources from local contractors to support the "core" sewerage operational crews helps to optimise deployment of key resources is essential in helping to minimise impacts of storm-induced events.

The requirement of the urban drainage system (in part) is the movement/removal or surface water via a subterranean network that is both gravity driven and pump driven in some locations. The pumping of water within the urban drainage system are the components that have interdependencies on other services, in particular telecommunications and power supply whereby failure of these services can potentially have detrimental consequences on the urban drainage network.

As part of the analysis within RESCCUE, the risks associated to the waste-water services and infrastructure in relation to their dependency upon the **energy** and subsequently the **transportation** networks to access, supply and maintain redundancy assets will be evaluated. This is achieved through the analysis of flood model outputs from the 2D modelling component relative to the other CIs within the case study area. For the Bristol case as an example, the National Receptor Database provides details as to the locations of substations throughout the city of Bristol; this data coupled with pump station locations and transportation networks (Figure 11) provides a basis of assessment for assessing cascading impact risks within the city.

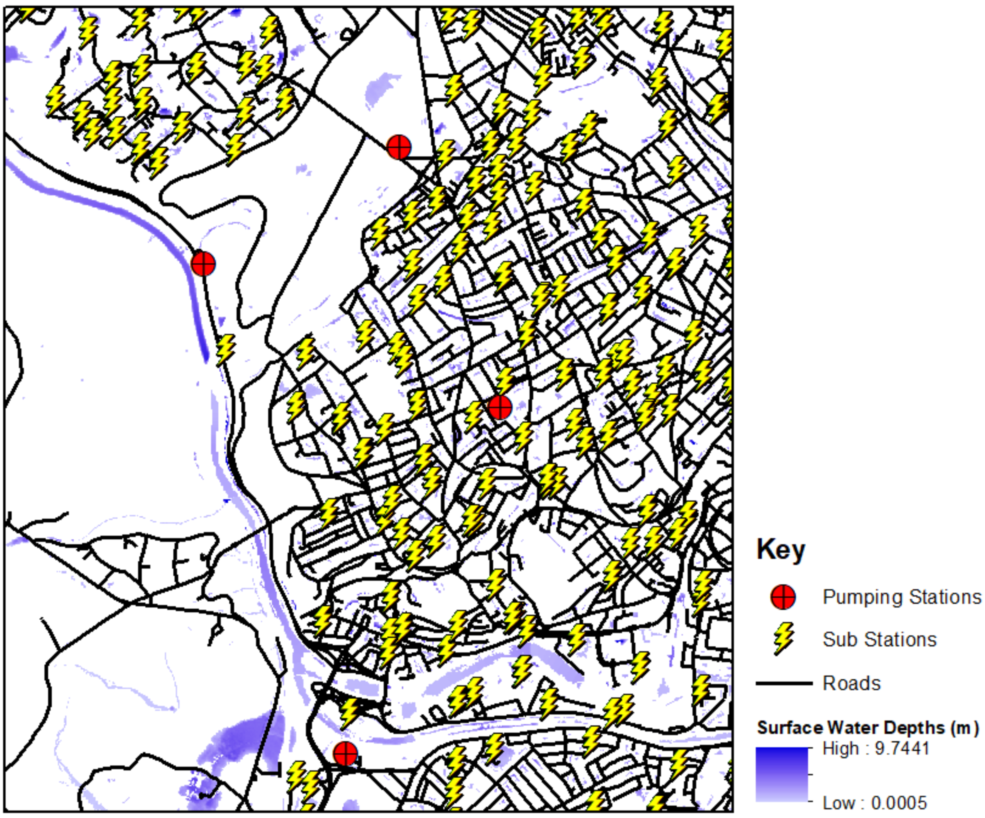

Figure 11 – Surface flooding from 1 in 100 year rainfall flood event overlaid relative to selected CIs within the city of Bristol.

As an example analysis of a selected 1 in 100 rainfall even within Bristol results in a certain degree of surface water flooding. Although this flooding does not directly impact the Pumping stations as shown in Figure 11, the proximity and depth of the flood waters do encroach onto region where substations are present. Using a Thiessen polygon approach (described in section 3.1.2 later in document) to define power supply zones by substations reveals that one substation may in fact lose power (Figure 12). In addition to this potential loss, as Figure 12 highlights, there are a number of substations that could potentially fail. The failure of such (as outline earlier in section 2.1.2) could put strain on the energy grid and lead to further cascading failures. In addition to the potential loss of power supply, we also observe (in Figure 13) some of the road network is flooded during the event that can lead to potential disruption of traffic flow. The duration of which traffic flow is affected could hinder the re-supply of fuel to any backup generator being used by the pumping station and also hider repair efforts to the impact substations within the affected areas. Thus although this particular flood event may not indirectly affected the pumping station, it may still be taken offline as a result of cascading failure within the energy network and potentially affected by traffic disruption. Failure of the pumps either directly or indirectly due to loss of power could result in pollution of the watercourse via the emergency overflow, or flooding at (or upstream of) the pumping station. If a pumping station is affected by power failure it may be necessary to consider actively managing upstream pumping stations to minimise the flow arriving at the failed station. Like that within the power network, the failure of one component within the water network can put additional strains and pressures on other parts of the network.

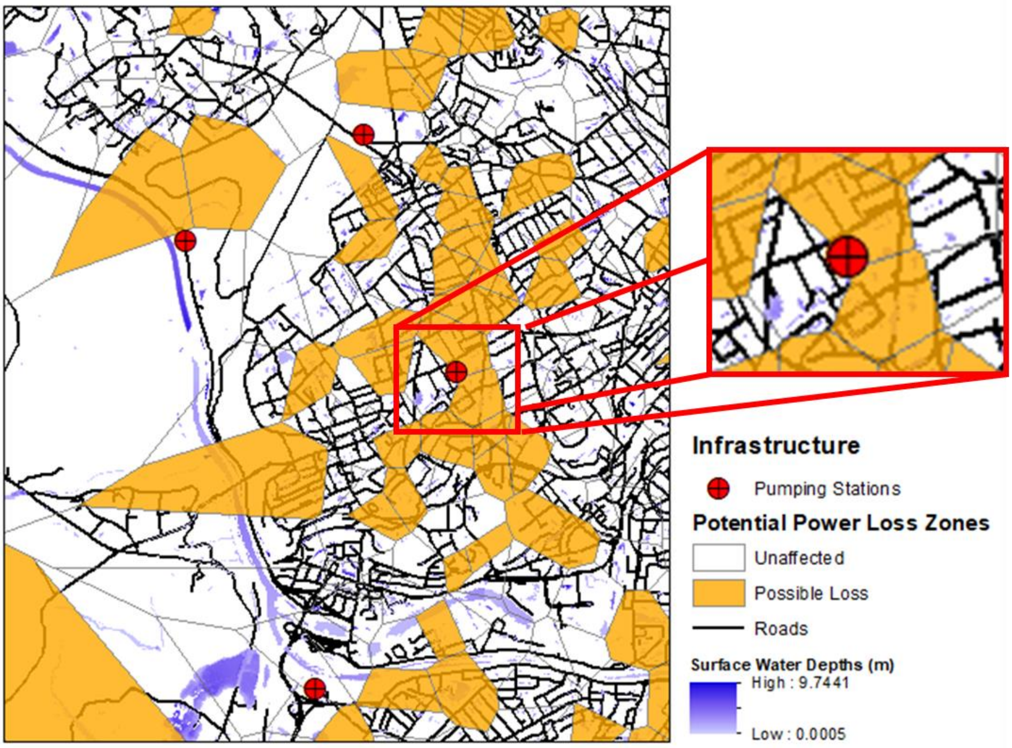

Figure 12 - Potential power loss regions due to a 1 in 100 year rainfall event

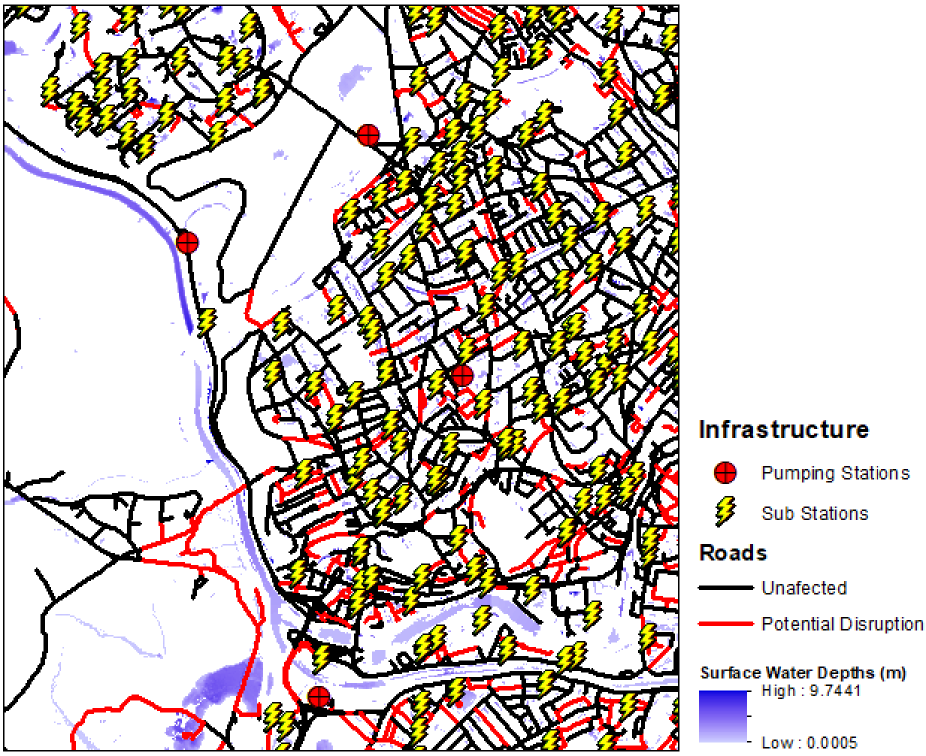

Figure 13 - Potential disruption to traffic flow during a 1 in 100 year rainfall event

2.3.1.1 Cascading failure in relation to CSOs

Within some situations where the sewer system is under increased pressure from a climate driven event (or through combination of climate event and technical failure) a CSO event may occur whereby excess untreated waters are allowed to directly discharge into natural water bodies such as rivers and waterways and/or directly out to sea. These CSO events can pose significant impacts on both human health and the environment. Within the city of Barcelona the marine model being employed aims to assess the quality of water along Barcelona's sea front during potential CSO events and estimate E. Coli concentrations following such events. . Previous work with the PEARL Project linked water quality modelling with Quantitative Microbial Risk Assessment (QRMA) to estimate the risks of illness through contact with contaminated waters. This approach can be employed to assess direct intangible effects to public health and additionally indirect economic effects as a result of business interruption.

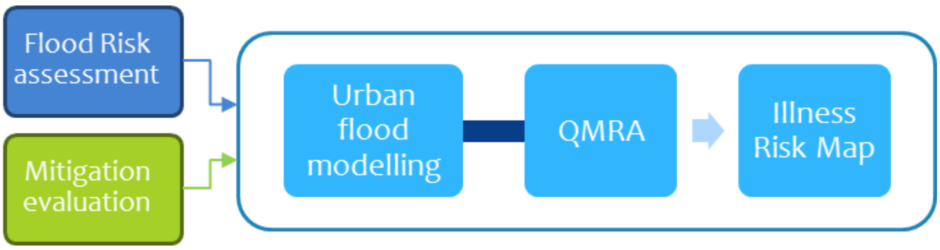

Figure 14 - Improved public health framework proposed and developed in PEARL

2.4 Cascading failures and risks within the Waste Sector

One of the main research efforts regarding climate change-related impacts on the solid waste sector is focused on offering mitigation measures and strategies to reduce the waste greenhouse gases emissions. However, just a few research studies address the reverse problem of how climate change actually impacts upon the solid waste sector (Zimmerman et al., 2010; Winne et al., 2012; USAID, 2012, 2014, 2015).

All of the case study areas have an extensive municipal service in place for a daily collection of household and commercial waste to provide waste collection to citizens and ensure a clean and healthy public space. These services are carried out through management of street containers, door to door bags collection service, pneumatic collection boxes and bins for collection in shops. Waste which cannot be placed in conventional containers is delivered to "Green Dot" collection points. Citizens also have special services regarding waste collection, such as old furniture and clothes, dead animals, debris bags gardening waste, fibrocement or asbestos. Taking part in the recycling waste collection is the first step in dividing household waste and a civic gesture, which contributes to preserving the environment. Waste can be reused via recycling, so it can become a resource and provide environmental and social benefits for everyone. In the context of public awareness campaigns, Barcelona City Council is promoting actions and tools to accompany the citizens in improving household waste collection through educational activities and training, which are addressed at the public and groups from the city.

Barcelona opts for a recycling collection including five different classifications of waste containers (Glass, Organic, Packaging, Paper and Cardboard, and General Waste). There are containers for each classification distributed citywide to make waste management easier. All citizens have recycling collection containers located less than 100 meters from their home (Figure 15).

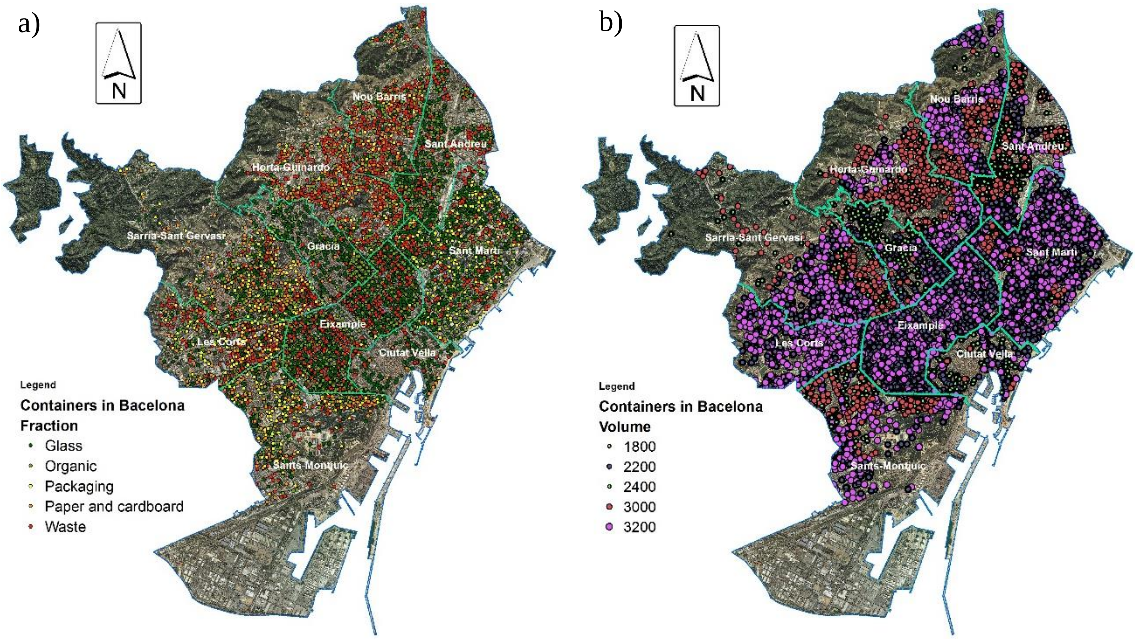

Figure 15 - Containers distribution in Barcelona classified according to a) Fraction type, and b) Volume (*Note: due to the great amount of containers, in some cases a dot indicates a location for a set of even five containers of different fractions/volumes. Therefore, within the map only a type of container, either classified by volume or fraction, is represented for each dot.*)

The methodology proposed here is the study of the stability of the containers when exposed to urban pluvial floods distributed across the city. In order to do this, three main stages have to be carried out:

- **1D/2D coupled hydrodynamic model**: Initially, an all-city drainage system model (1D) together with the overland streets model (2D) has to be performed by employing historic or synthetic design storms related to different return periods.

- **Stability functions for waste containers**: These functions have been developed based on an analysis of forces acting on a flooded container by establishing equilibrium conditions for the different modes of instability (i.e. sliding, toppling and floating) (Figure 18). These functions depend on both hydraulic variables, velocity and water depth. Moreover, the characteristics of each container (e.g. volume, dimensions or fraction they may contain) determine the shape of each function. The obtained stability thresholds were employed to analyse the potential behaviour of containers against floods in Barcelona caused by historical and low-return-period design storms (i.e. 2, 5 and 10 years)

- **Georeferenced containers location**: The Barcelona City Council performed a GIS-based map with the location of all types of containers across Barcelona City. This information is essential to identify if their current location may lead to a potential instability.

Therefore, the resulting outputs from the hydrodynamic model (i.e. velocities and water depth within the studied domain) have been related to the containers and by applying the derived stability functions, those containers potentially unstable have been identified. Adaptation measures to improve the resilience of waste sector against urban floods (i.e. sewer or pluvial floods) in Barcelona will be proposed based on the investigation of the stability behavioural of containers exposed to flooding in Barcelona.

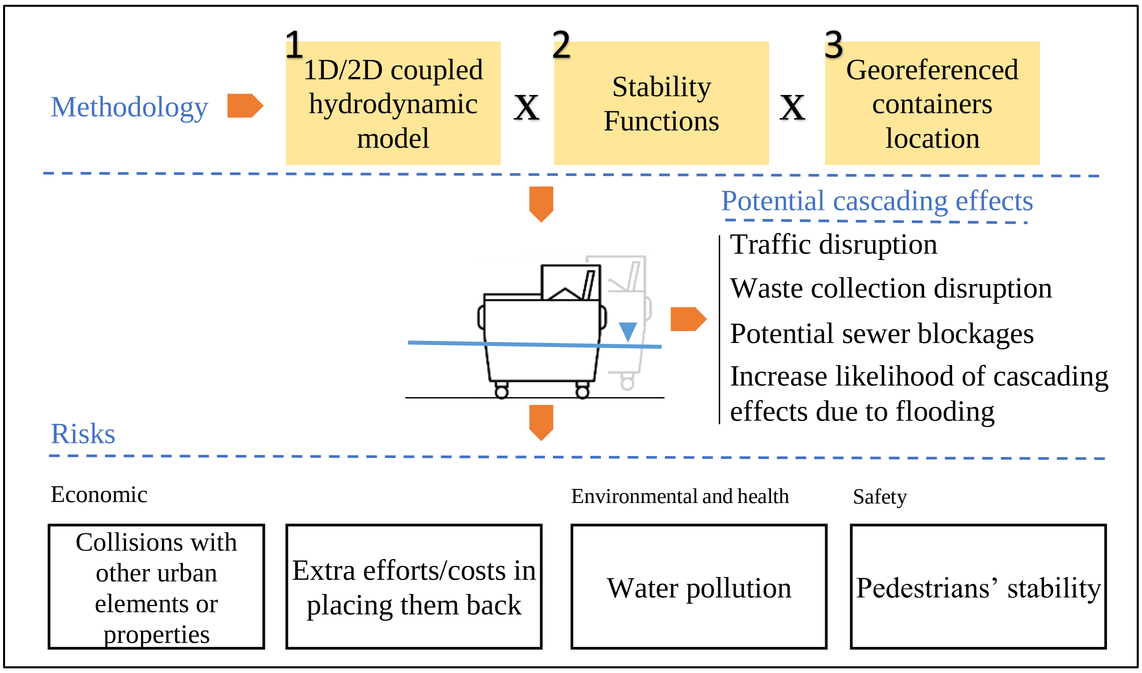

Figure 16 - Methodology workflow and Potential cascading effects and risks related to containers instabilities

2.4.1 Cascading effects in the waste sector

When an urban flood occurs waste containers may lose their stability, thereby allowing debris (i.e. solid waste contained) and leachate to escape from the container and contaminate the floodwater. In the case of larger flood events the container itself may also be washed away (i.e. a massive debris) together or separately with its content (Figure 17 and Figure **18**). Such types of massive debris carried by floodwaters, like that of vehicles (Martínez-Gomariz et al., 2018), can further constrict a narrow street and increase flooding, thereby creating a closed basin with no or limited outlet for runoff and exacerbate the effects of flooding. When this occurs, the likelihood of potential cascading effects due to urban floods increases and this hazard is greatest upstream of culverts, bridges, or other places where debris can collect. On the other hand, inlets and sewers may become clogged with solid waste if it comes out of the container after it loses stability, thereby worsening the drainage system and contributing to exacerbate the flood impacts (i.e. more direct and indirect damages). In consequence, the waste containers stability when exposed to flooding is definitely an environmental, safety, health and economic concern that needs to be addressed.

Figure 17 - Real containers instabilities due to flooding in Barcelona

The main cascading effects due to containers instabilities (in summary) can be listed as follows:

- **Traffic disruption**: Traffic may be disrupted not just while flood is occurring but also after the event when these containers that were washed away may be laid in trafficable locations.
- **Waste collection disruption**: After a flood event, the waste collection may be disrupted if containers were moved from their original location. The municipal workers have to relocate them and even collect their content in case it came out from the container after losing the stability.
- **Potential sewer blockages**: Potential debris coming out from the container may block inlets and sewers and thereby affecting the drainage effectiveness.
- **Increase likelihood of cascading effects due to flooding**: If containers moved from their original position lay at narrow streets, water depths may increase and therefore the flood consequences will be aggravated. A flood without important consequences may turn into a flood which causes a cascading effect to other sectors such as that highlighted earlier in Figure 1.

Figure 18 - Effects of containers instabilities.

2.5 Methodology for assessing cascading effects on Transportation Sector in case of flooding

In the three RESCCUE research sites, different approaches for their own subsequent traffic modelling are being used based on local needs and expertise within the respective cities. Therefore the proposed methodology for quantifying impacts of climate driven events and their consequences on other sectors has been designed to be transferable as a “loosely coupled” model/methodology approach as depicted in Figure 19. The GIS spatial analysis component of this model looks at the vectorised flood extents within threshold water depth and velocity ranges and their intersections with components of the transportation network. This information can be used either directly to give indication of level of disruption to the mode of transport or (in the case of the road network) used as input data in traffic models for further analysis.

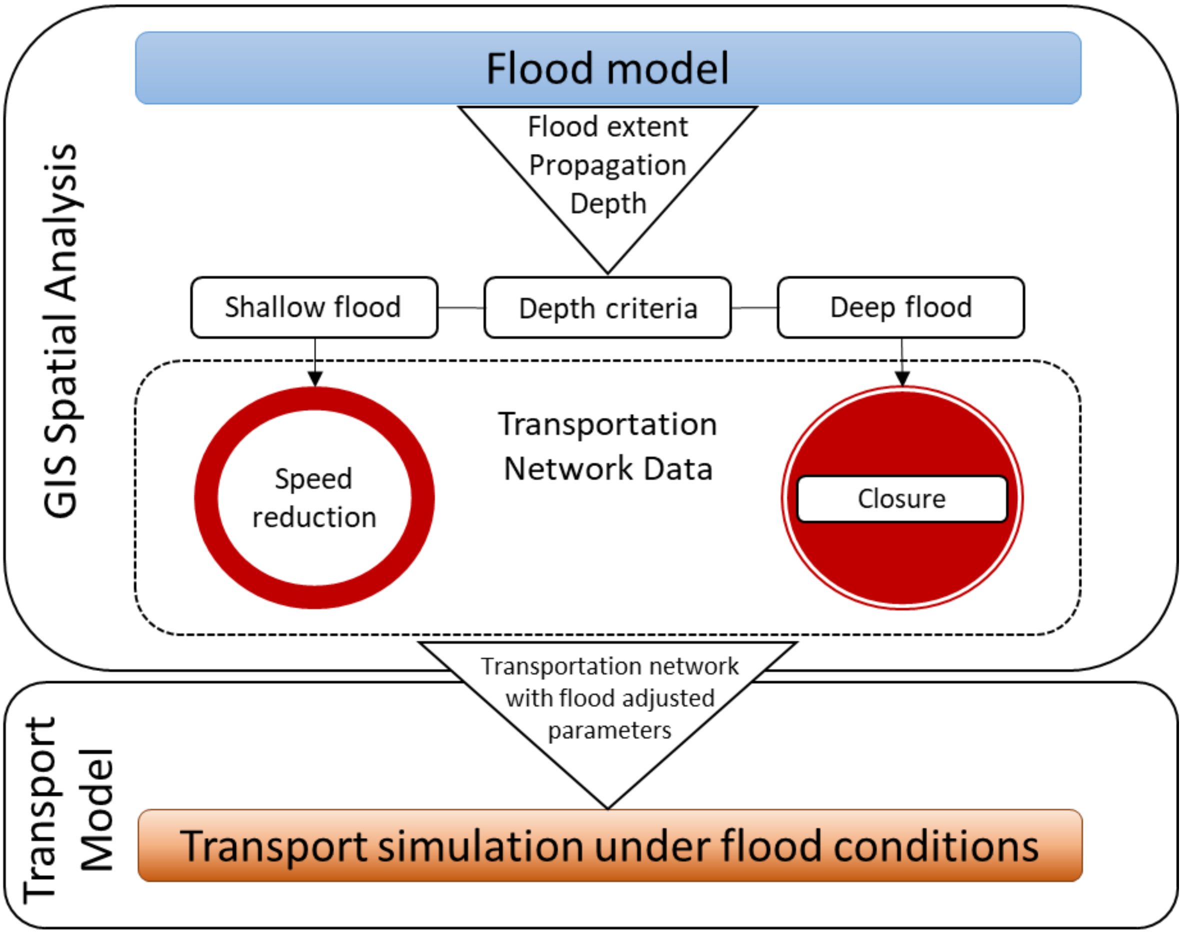

Figure 19 - Loosely coupling flood model outputs with transport model inputs

2.5.1 Micro-scale traffic model

The proposal for the Bristol case study is to utilise the SUMO (http://sumo.dlr.de/index.html) micro-scale traffic model that simulates traffic flow within a road network at the individual vehicular level.

The data inputs used in the micro-simulation models within SUMO come from OpenStreetMap. This data is freely available and contains detailed information about the road network relating to speed limits, permitted directions of travel and traffic control systems (e.g. traffic lights and crossings). Within OpenStreetMap however the roads are depicted as single entities thereby simple spatial analysis such as intersects of floodwater with the road network would result in closure of the whole road after analysis (regardless of its length or where flooding occurred) which may not reflect the impacts to the network in reality. For this reason, a pre-processing step of dividing the road into sections (links) is used. For example, the original road network taken from OpenStreetMap for the city of Bristol (Figure 20) is represented by 21,246 line features, converting this network to links results in a network now consisting of 43,209 line features that corresponds to a 103% increase of features.

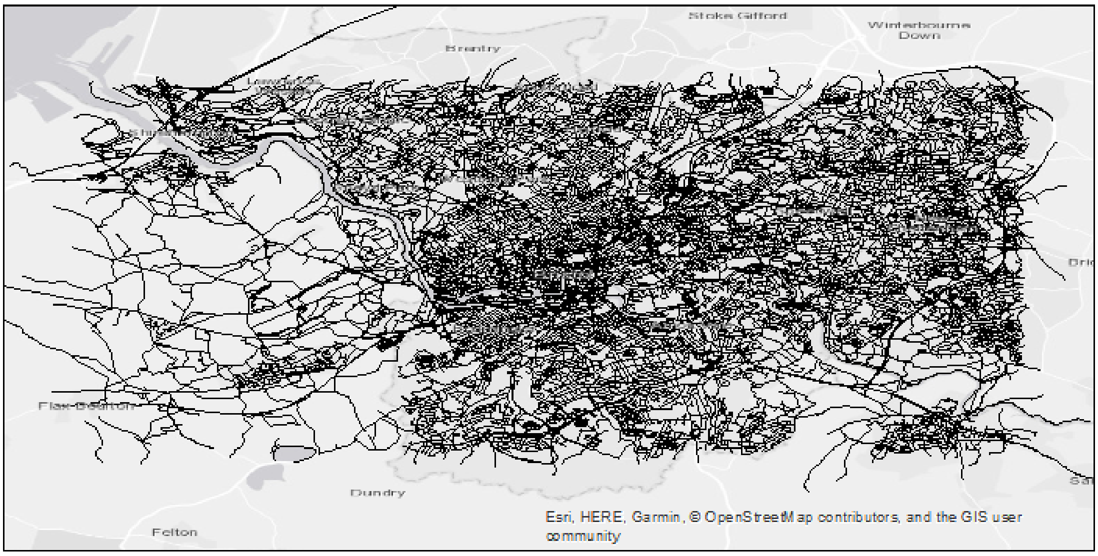

Figure 20 - Road network within Bristol

2.5.2 Meso-scale traffic model

Within the city of Barcelona a meso-scale traffic model (TransCAD®) modelling software (https://www.caliper.com/tcovu.htm) is used for the simulation of traffic demands on their road network. The road network data inputs for the meso-scale model are already subdivided into links/sections. In contrast to the micro-scale model whereby individual vehicles are simulated, within the meso-model each link/section contains information relating to road properties and traffic flows along that link/section in a tabular format. The properties of these link/sections can be altered within their tables with respect to the flooded conditions of the roads and then traffic flows can be simulated accordingly within the meso-model.

2.5.3 GIS based analysis traffic modelling

The 3rd approach (used to model the effect of flooding events on traffic in Lisbon) takes advantage of the data available allowing the analysis of the whole city. The approach being adopted is a citywide GIS-based surrogate model, making use of available information and results from flooding, thus allowing obtaining results to decision support on course of action to face expected effects of climate dynamics.

The main outcomes of the GIUS analysis are to define urban areas exposure and transport sector critical components for each scenario analysed and estimation of broad impacts on the service. Information from historical events is taken into account to complement the hazard maps, namely with regard to range of water levels expected in different locations. Effects of hydrological processes on infrastructure and the risk of flooding are also analysed.

2.5.4 Quantification of impacts and cascading and disruption to the traffic network

The effects of a flooding within a given location in road network are not solely located within the immediate location as (depending on the location and duration of the flooding) the consequences of disruption at a given point can propagate throughout the road network and cause major wide scale disruption to traffic flow in addition to impacting other services that are dependent upon the network.

As part of work within the PEARL (outlined by Pyatkova, 2018) they defined that the property of flooded roads within a city network in 3 possible states:

1. **Flood water level below speed reduction threshold value:** Road unaffected.
2. **Flood water level equal to or above speed reduction threshold but below road closure threshold value:** Maximum permitted speed along road reduced.
3. **Flood water level equal to or greater than road closure threshold value:** Road section/link closed.

Utilising these rules a GIS based approach can be employed to analyse and quantify the impacts of flooding upon sections/links within the road network. Figure 21 shows an example of the effects of flooding on the maximum traffic speed along road links due to the level of standing water present with the rules/thresholds on speed limitations defined as in Table 3. These impacts can then be analysed with respect to both local services and infrastructure that are dependent upon these roads or the information can be fed into a dynamic traffic model.

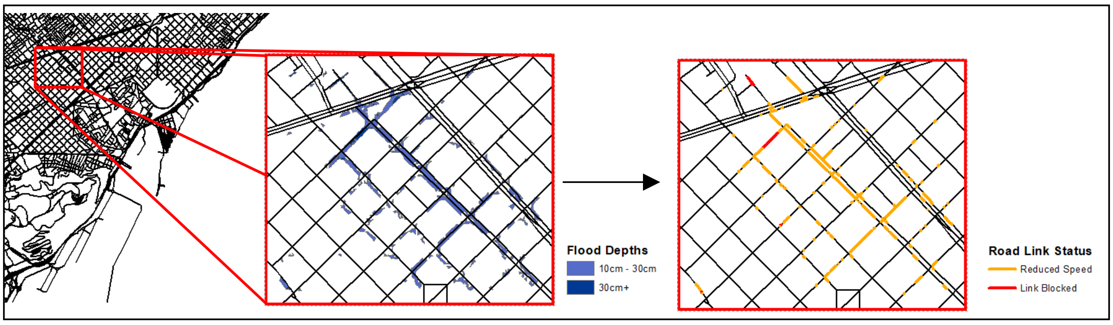

Figure 21 - Quantifying impacts on links within road network

Table 3 - Impacts of flood-water on tradffic flow along roads sections

Flood Depth Range (cm)	Maximum Permitted Speed kmh^{-1}
0.00 – 10.00	*No effect - Roads maximum speed*
10.00 – 30.00	20
30.00 +	0 (*Link closed*)

Flood impacts on transportation can be quantified in terms of disruption to traffic through increased journey times and/or increased journey distances and subsequently monetised through estimated loss of earnings.

At a city wide level, the disruption to traffic flow from a given flood event can be expressed in terms of number of vehicles within the network in comparison to dry weather scenarios within the same time frame. Figure 22 shows the impact a rainfall event can have on a road network (at network level resolution) in morning traffic during an extreme rainfall event that lead to some flooding. Here it is possible to observe that because of flooded roads, the number of vehicles that remains present in the network increases. The increase in travel time is due to the increase in respective journey times due to both speed reductions and/or road closures that require re-routing of traffic within the network.

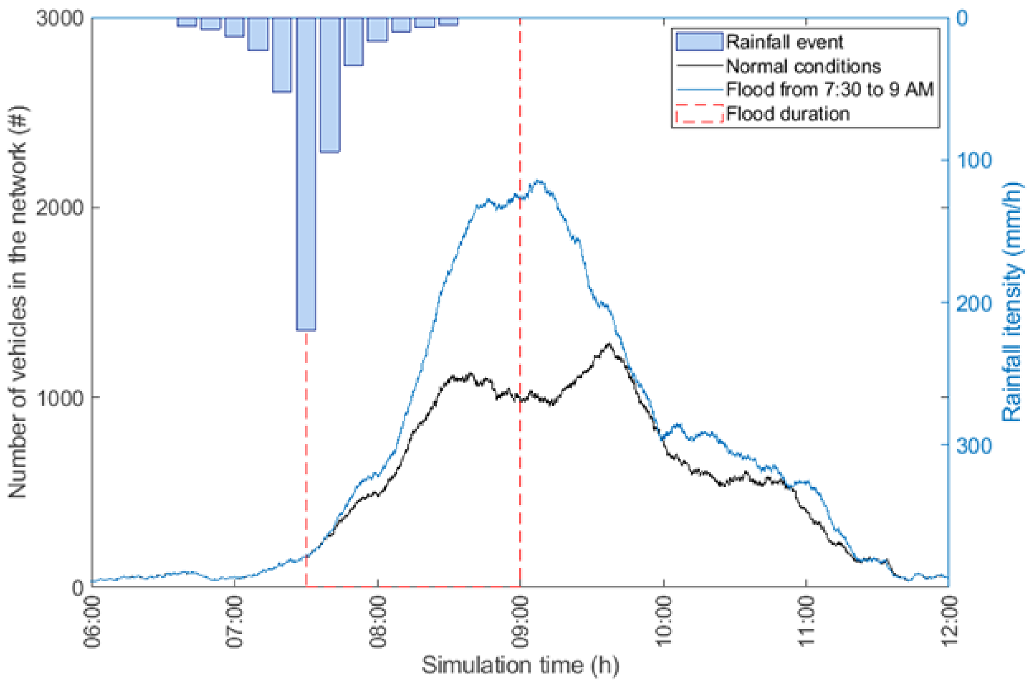

Figure 22 - Number of vehicles in network during normal and flooded road conditions in morning hours (Pyatkova, 2018)

Table 4 - Differences between normal and flooded conditions in morning traffic for 24 hour simulation (PEARL)

	Normal conditions	Morning Flooding	Absolute change	Change (%)
Depart delay (h)	16,207	16,922.7	715.7	4.4
Duration (h)	7,870	9,064.6	1,194.6	15.2
Travelled distance (km)	202,256.5	205,094.1	2,837.7	1.4

2.5.4.1 Quantifying impacts of traffic flow disruption to other services within cities

In the context of specific key services within the city the localised impact on traffic flow will be examined. In these cases the performance of such infrastructure that is dependent upon traffic flow will be compared relatively to that of dry weather traffic flow conditions.

The reduction of free-flow travel times along certain sections of the road network not only affects the flow of traffic within the flood region but also cascades outwards throughout the road network from the immediately affected areas. Road closures and the subsequent disruption to traffic flow can pose significant problems to services that are dependent upon such services the level of disruption can be classified in two ways:

Service disruption: In this instance due to areas of the transportation network being flooded the loading on the road network in certain locations is increased resulting in either increased journey times and/or longer journey routes.

Service failure: Due to breakdown in the network the service to a specific regions may no longer be possible due to lack of access via the transportation network.

A cascading effect example of service disruption could be that like which was highlighted earlier in Section 2.4, whereby the functionality of the waste sector within cities is dependent upon the removal and transportation of waste. In addition to the direct impacts that flooding can have on waste there are indirect consequences caused due to failure of the transportation network that may prevent or restrict the removal of waste from receptacles across the city and/or the removal of household waste if flooding events coincide with collection days. The failure of waste removal from city's can result in increased risks of vermin and pests within the city and pose risk to human health if waste disposal is not managed in a timely manner. In addition to these risks, unmanaged waste may find its way into the drainage network resulting in a decrease of the city's drainage capacity leading to increased likelihood of flooding in future events. Tangible impacts in this example could be related to the increased cost on fuel required due to increased journey times and/or distances covered by collection vehicles and more indirectly (in relation to public perception) the loss of trade whereby increase trash volumes discourage individuals from frequenting certain areas. There are other quantifiable impacts of such events that are more complicated than that of usual damage based approaches to evaluate such as the effects on human health, the perception of the city (lost confidence) and increased stress to residents in the community. These type of damages are referred to in some literature (Jonkman, Bočkarjova et al. 2008; Ranger et al. 2011) as indirect intangible damages.

2.5.5 Other modes of transportation

The methods outlined above focussed upon quantifying impacts on transportation via vehicles traversing the road network. The modes of transport within cities, however, are not limited to the road network but also include rail, air and water. In these instances the level of direct impact are determined at the GIS spatial stage of the workflow and indirectly relative to loss of services required for this particular service to function (e.g. loss of power to train signalling resulting in temporary failure of the rail network).

2.6 Summary assessment of cascading effects across services

The previous sections have highlighted some of the identified interdependencies and redundancies in place for each of the selected Critical Services being investigated within RESCCUE. The complexities of some of the interdependencies and potential chain of cascading service failures are highlighted in Figure 23. Here the solid red arrows depict potential direct impact of event to a service and red dashed arrows represent indirect potential positive feedback to the flood event. The solid blue arrows represent the service dependencies and the dashed blue arrows represent link to possible redundancy equipment that may be employed. The stopwatch symbols are included to highlight that if redundancies are in place the service may still be able to function for a period of time.

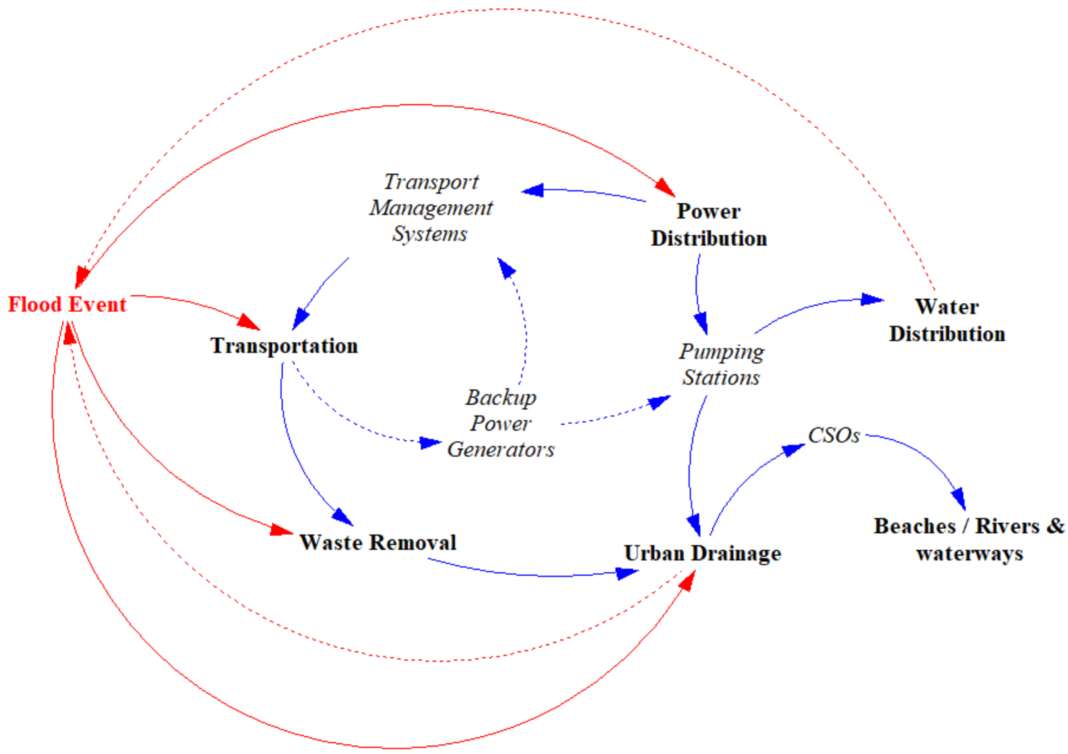

Figure 23 - Example of generalised complex chain of cross-sectional interdependencies between services

The methodologies used to estimate impacts on each of the identified services are primarily carried out in silo with respect to the service being analysed, in order to fully represent the possible cascading effects that result across all connected services. The following section expands upon what has been highlighted and proposes both physical and holistic based solutions to combine the models used for different services.

3 Physical and Holistic based modelling approaches for analysing cascading effects between different service sectors

The physical based model approach in this context is based on analysing the effects of an impact at regional, sub-regional, zonal and infrastructural levels. Within a detailed modelling approach, it requires defining the services that are both provided (donor) and required (receiver) between critical infrastructures in order for a city to function as designed.

Previous sections of this document have highlighted how impacts can affect services, the interdependences on other services and, in some instances, the redundancies and mitigation measures that can be put into place. This section of the document shows the means in which models used to analyse impacts on different services can be linked to examine cascading effects.

3.1 Defining Interdependencies

The failure of a service provided by an infrastructure either directly (due to impact on infrastructure) or indirectly (as a result of service failure upstream) can have detrimental consequences on other infrastructures and services further downstream in the supply chain. For example (as highlighted earlier in Figure 1) the failure of a substation could result in the failure of a pumping station as part of a water distribution network thus resulting in loss of water supply within a region.

The analysis of interdependencies introduces the notion of cascading effects, defined as the impacts of a given trigger event in the case where the dependencies from the system lead to the propagation of impacts to other systems, where the combined impacts of propagated events have greater consequences than the first impacts, and where multiple stakeholders are involved (Ekman & Lange, 2014). The resulting interdependencies and cascading failures greatly increase the vulnerability of the whole urban system. To accurately define interdependencies between two or more infrastructures whereby one is providing a service to another, expert knowledge about the service and infrastructure is required; in the context of this document, this is known as a “Direct Known Interdependency”. Due to sensitivity or lack of access to critical infrastructure data however, the derivation of direct known interdependencies may not always be possible and the unknown relationships between donors and receivers in this instance have to be derived via another means with the use of assumptions. The types of interdependencies are subsequently classed as “Direct Unknown Interdependencies”.

3.1.1 Direct Known Interdependencies

The earlier sections of this document outlined the dependencies between services being analysed in RESCCUE and records of potential cascading effects during service failures. Using the methodologies outlined earlier within this document, the results of simulations of various hazards in the three research sites produced in WP2 can be used to assess a variety of impacts (WP3), for a range of climate driven scenarios (WP1).

The interdependencies of a receiver infrastructure to a donor infrastructure/service, if the information is enough, can be physically defined via a linked table based approach. Figure 24 shows a simplistic scenario of one substation providing power from the grid to 4 properties. In this example the interdependencies between substations and properties can be defined via associating the houses' IDs with the substation's ID in a link table (Figure 25). This approach allows for more detailed GIS based analysis whereby if a given infrastructure is impacted by a climate driven event the impact on infrastructures (receivers) that are dependent upon that service can be derived.

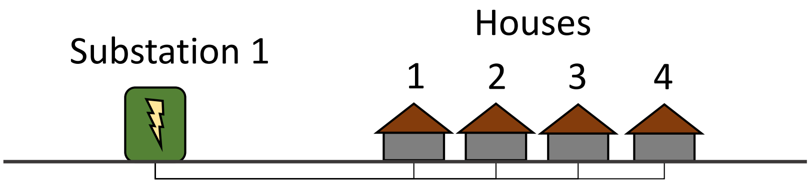

Figure 24 – Example of defining interdependency of power supply to properties.

Houses table

House ID	Address
1	1 Bristol Road South
2	2 Bristol Road South
3	3 Bristol Road South
4	4 Bristol Road South

Substation table

Substation ID	Name
1	Bristol Centre
2	Ashton 1
3	Clifton 1
4	Redcliff

Link table

House ID	Substation ID
1	1
2	1
3	1
4	1

Figure 25 – Linked table approach for interdependency impact analysis.

3.1.2 Direct Unknown Interdependencies

In the absence of detailed information relating to the donor and receiver relationships between critical infrastructures, a "fuzzy based" approach can be applied (Evans et al., 2018) (Figure 26).

Figure 26 - Estimating cascading effect of service disruption resulting from pipe burst flooding event leading to power disruption (Evans et al., 2018).

This approach looks to represent interdependencies based the likelihood that one CI is receiving a service provided by a donor CI. This style of approach uses spatial zonal analysis to define service area zones, where the likelihood of an infrastructure receiving a service from a donor is proportional to the distance from the donor infrastructure. Figure 27 shows an example of how zonal analysis is applied where information is lacking to determine likely service area zones. Figure 27(A) Represents the true donor to receiver relationship with a priori knowledge obtained from fictitious service providers whereas in Figure 27(B) it is assumed that the information linking donor to receivers are unknown. For the case of Figure 27(B), utilising spatial analysis (in this case a Thiessen polygon approach) assumptions are made of the interdependencies based on the likelihood that an infrastructure is receiving a service from a donor infrastructure is proportional to its distance from said infrastructure. In reality this spatial relationship may not always be the case (as highlighted by the differences between approaches in Table 5 and other factors need to be considered; but in the absence of expert knowledge, a spatially based approach provides a good starting point for defining likely interdependency links.

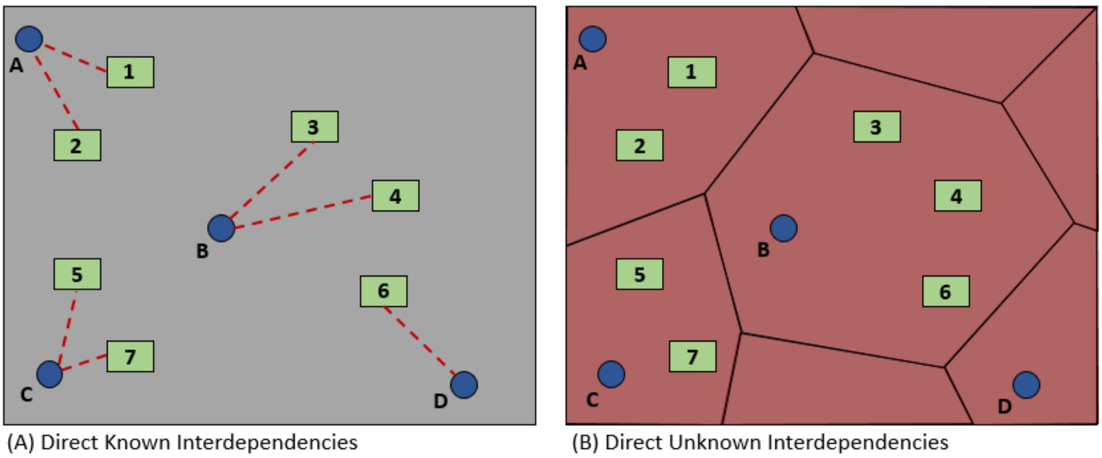

Figure 27 - Comparing Known and Unknown Interdependencies.

Table 5 - Comparative view of defining known and unknown interdependencies.

		Direct Known Interdependencies							**Direct Unknown Interdependencies**						
		Receivers							**Receivers**						
		1	2	3	4	5	6	7	1	2	3	4	5	6	7
Donors	**A**	**x**	**x**						**x**	**x**					
	B			**x**	**x**						**x**	**x**	**x**		
	C					**x**		**x**						**X**	**x**
	D						**x**								

3.2 GIS tools for direct, indirect and cascading impact assessments

Impacts upon infrastructures and subsequent services are primarily dependent upon the spatial distribution and magnitude of the hazard. Deliverable 3.2 previously showed the means used in defining magnitude of impacts in relation to depth damage and fragility curves for flood events and it is this style of approach that is used for the initial triggering impact when analysing cascading effects. Hazard maps produced (as defined in Deliverable 2.2) will therefore be used for their respective city areas as the basis of determining the magnitude and location of impacts on infrastructures and services.

Previous work within EU-CIRCLE developed GIS based tools that enable the analysis of impacts on infrastructures derived from time-series flood depth data using a physical based modelling approach. The methodology employed here looked at loosely coupling models to assess service status and potential feedback loops (Figure 28). This approach is comprised of two feedback loops whereby the first loop is focused on a particular asset within a critical infrastructure network (e.g. substations as part of energy supply service) and the secondary loop examines the potential cascading effects as result of service disruptions. Once all assets and cascading effects are analysed a summary of impact is produced.

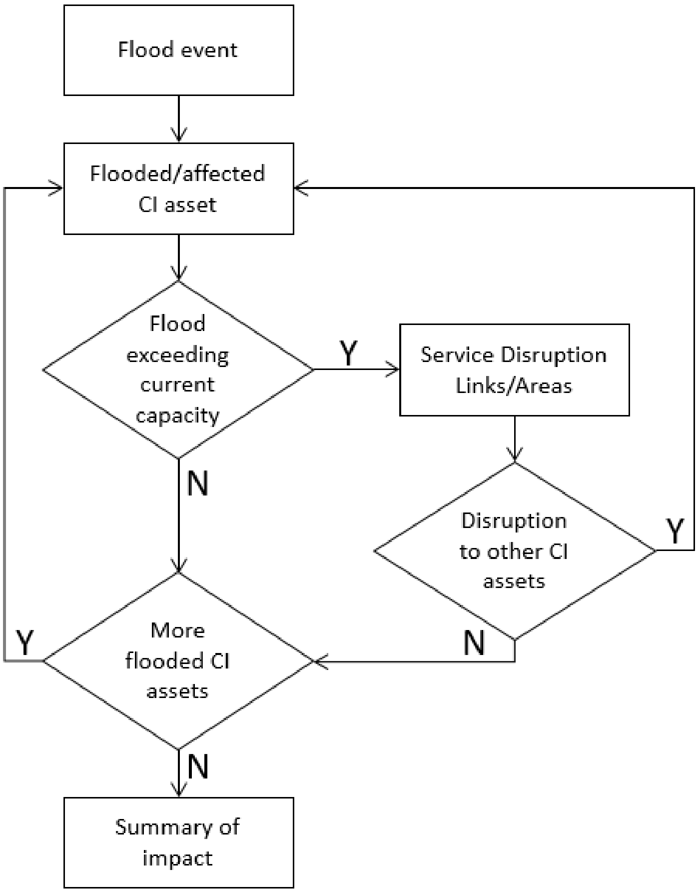

Figure 28 - Flowchart of Physical Based modelling approach of assessing cascading impacts

Within this analysis process the interdependencies between infrastructures and services needs to be defined. The method proposed in RESCCUE is to define these interdependencies via utilising a linked table approach (as shown previously in Figure 25) whereby information about the dependency type (known or unknown) is also defined. Impact based analyses can then be carried out within the case study areas and affected infrastructures can be identified. Figure 29 shows an example of the approach outlined in Figure 28 applied in the EU-Circle project to assess both direct impact and indirect (as a result of power failure) impacts. Here the indirect impacts are presented via "Electricity Disruption Zones"; these zones can be defined either as known or unknown/assumed regions depending upon data availability.

Figure 29 - Various CIs with direct and indirect (as a result of power loss) impacts as a result of of a flood event (EU-Circle)

3.2.1 Temporal considerations of cascading failures

Cascading failures of critical infrastructure do not often occur instantaneously but do so over a period of time due CIs having certain levels of protection and/or redundancies in place to prevent/minimise the likelihood of such failures. It is therefore important to consider temporal properties of any given hazard, the types of redundancies in place, and the downtime and recovery time of CIs. For example the continual effective operation of critical components within the urban drainage system is dependent (in part) upon **electricity supply** for the sewerage pumping stations. To minimise the risk of failure of these pumping stations the following mitigation strategies are employed:

- **Dual Power Supply** being provided to critical pumping stations (whereby supply is fed from two separate electricity suppliers with entirely separate infrastructure and with automated changeover). This is the case for Ashton Avenue Sewage Pumping Station in Bristol
- **Permanent generator**(s) which provide back-up electricity supply in the event of failure of the mains supply. All major (strategic) pumping stations will have standby generation – e.g. Class C.
- A power connection facility to allow a **mobile generator** to be brought in where needed

In some cases the **mobile generator** may be adequate to only operate the duty (dry weather) pumps and not all pumps present at the station. Performance during wet weather may therefore be compromised. The reliance of both **mobile** and **fixed** generators can be additionally affected by flooding if the transportation network is compromised as:

- Roads may be blocked by the floodwater itself or by backing up of traffic / abandoned vehicles as a result of floodwater or damage to highway. It may not be possible to deliver and connect the mobile generator in time.

- Mobile generators must be visited periodically to check operation and keep it supplied with fuel. Mobile generators will normally have a fuel supply sized to provide at least 8 hours running at full load rating
- Fixed generators also require fuel to operate. Within Wessex Water, fixed generators will normally have a bulk fuel tank sized to provide 72 hours running at full load rating

The duration of a hazard is of particular importance for the transportation perspective whereby it takes the transportation network a while to recover after a flooding event (as highlighted previously in Figure 22). Within the context of the road network such delays could potentially prevent or delay the recovery of critical infrastructures or vital components such power generators that would require re-fulling to keep redundancies in operation.

In addition to the time element playing a factor in the cascading failure of services it also affects business operations either through delay of arrival of key personnel as a result of transport infrastructure failure, the temporary inability of a service to function as a result of loss of key service (such as water or energy supply), though diversion of resources where key personnel are required elsewhere to deal with impacts or through direct impact itself. The loss of time and therefore money for a business in this context is referred as Business Interruption.

3.2.2 Indirect Tangible Damages (Business interruption)

Unlike the costs associated with direct impacts as a result of an event, the failure of services can have indirect effects on businesses/infrastructures known in the insurance industry as business interruption losses defined as the loss or reduction of income due the suspension of operations as a result of an natural disaster (Grossi & Kunreuther, 2005). With direct known and unknown interdependencies defined, the impacts of a given hazard over time to businesses and residents can be estimated. The approach adopted for modelling indirect damage was outlined in PEARL (Figure 30). This approach utilises land use classifications as basis for quantifying business interruption losses along with losses as a result of traffic disruption. Within the PEARL project the traffic model used was the micro-simulation model SUMO; the monetisation of impacts on traffic however is transferable to all traffic models.

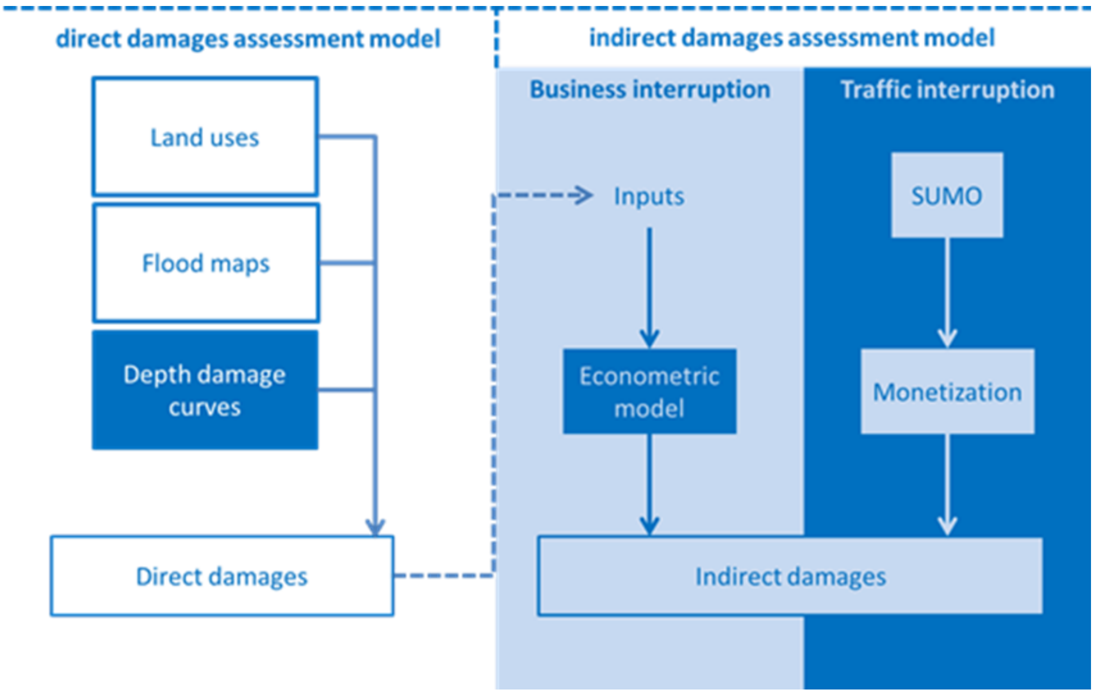

Figure 30 - Relations between direct and indirect damage models (PEARL)

With land use classification and interdependencies defined the overall impact in terms of both direct and indirect damages in relation to a given hazard.

3.2.3 Loosely coupled feedback modelling

As highlighted in earlier sections, the effects of a climate driven event on one service sector may have both direct and indirect impacts on another sector along with the additional consequence of increasing the overall impact of an event through a positive feedback loop.

Figure 31 shows a flow chart perspective of how a flood event can directly impact different services, how these impacts indirectly affect others and how it can lead to a positive feedback loop that exacerbates the hazard. The modelling component steps in this figure are represented by red boxes, the intermediate GIS analyses steps (used in loosely coupled feedback) by green boxes, and the dashed grey box represents an analysis that may be required under certain conditions; the solid black arrows represent direct impacts of flooding, the dashed greyed arrows represent potential cascading impacts/failures of one service as a result of impact/failure of its donor provider, and the dashed red arrow depicts the potential positive feedback loop component of the failure of the urban drainage system that may result in increased flooding. The key aspect of this approach lies within the impacts assessment methods as outlined in previous sections and how these impacts can affected other services.

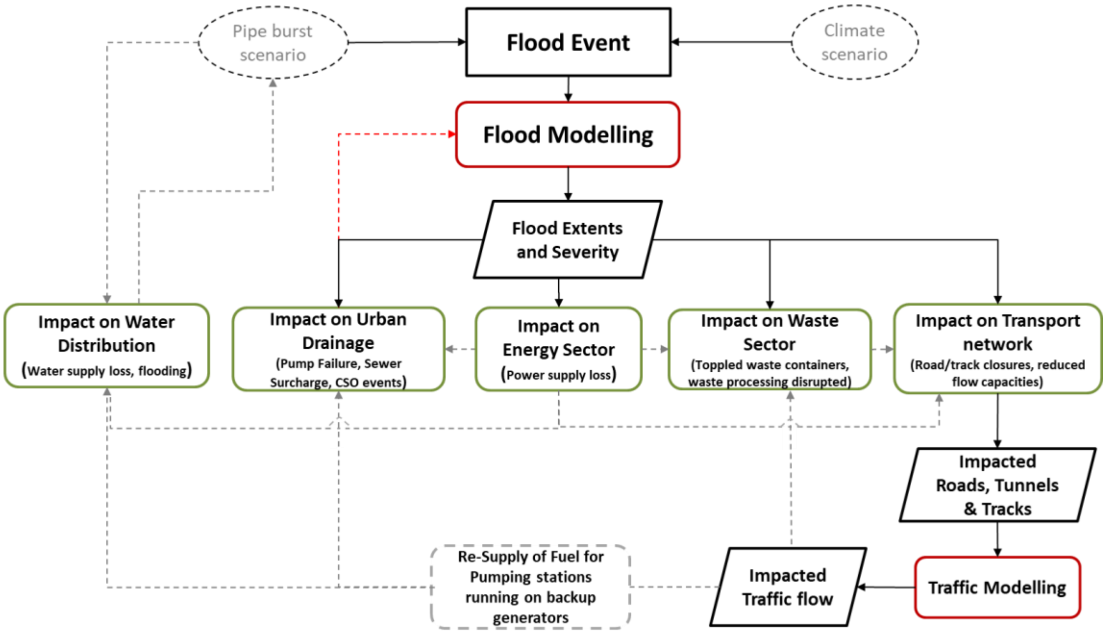

Figure 31 - Investigating cascading flood impacts across multiple services

Due to the intricate complexities in establishing the interdependencies between infrastructures and services, and accurately defining aspects such as the responders and redundancies in place the coupling of physical models can be a complex task. A potential solution to this is to utilise a combination of physical and holistic based modelling (along with stakeholder engagement) to derive an iterative methodology for more accurately assessing impacts.

3.2.4 Combining Physical and Holistic based approaches to capture cascading effects

An essential component within RESCCUE's workflow to facilitate this process is the HAZUR® tool. The HAZUR® tool in WP4 allows for the representation of multiple interdependencies of infrastructures and services and facilitates both the gathering of key information for impact analysis and also as a means of disseminating information to stakeholders.

In scenarios whereby the data quality is high the resilience of a city can be assessed in detail and simulations of the consequences of impacts can be analysed. In situations where detailed data may be lacking, however, the HAZUR® tool still allows for the flexibility of analysis of impact scenarios whereby the results can be presented back to stakeholders and encourage engagement/dialogue on ways of improving the model representation of their respective cities.

The combined physical and holistic approach to be used in RESCCUE is referred to as a cyclic approach and is depicted in Figure 32. Here, data about impacted infrastructures from a given hazard using physical based modelling can be fed into the HAZUR® tool and via the utilisation of a "What If?" based analyses the knock-on effects of impacted services and infrastructures on other services and infrastructures within the city can be assessed holistically.

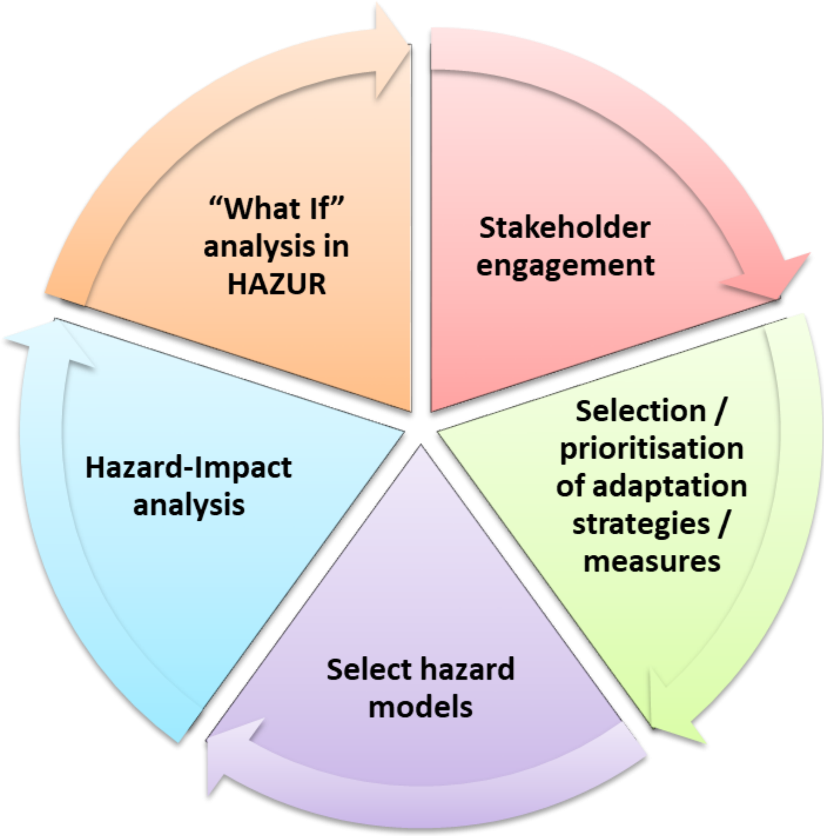

Figure 32 - Cyclic approach for stakeholder engagement and identifying cascading effects.

HAZUR® can help to identify, represent and understand interdependencies and cascading effects by gathering city information (including city services and infrastructures, localisation of infrastructures, interdependencies, redundancies, impacts, responders…). This can be implemented at different levels, with different scopes and spatial scales, and applied on a greater or smaller number of systems, depending on the goals of the implementation and the available resources and time. This holistic approach may largely be complemented with the models presented in this document. The main difference is the starting point. While most models are physical-based and/or based on the infrastructures themselves, HAZUR® proposes a holistic framework with a common model for all services. HAZUR® provides global information on foreseeable cascading effects, which can be complemented by more precise but more sectorial models (even if taking into account different types of infrastructures, such as urban drainage, electricity and traffic). This double approach allows flexibility and brings added value.

The HAZUR® tool will play a key role within RESCCUE whereby it will be populated with a detailed inventory of infrastructures, services and interdependencies within the city along with any redundancies. GIS based impact based analysis that is then carried out externally using the methods outlined in this document will then be fed into the tool via the "What If?" functionality, whose goal is to identify the direct consequences of an impact on the services and infrastructures. This will allow for a more comprehensive view of the consequences of given impacts and also bring to light potential cascading failures.

It is important to highlight that the HAZUR® tool is supported by the assessment methodology developed by Opticits, which is based on different research projects (Fontanals et al., 2012) and inspired by several international research works (Toubin et al, 2014). This collaborative approach incorporates the knowledge and the experience of the local stakeholders and networks operators (Fontanals, 2016; Toubin *et al*, 2014), via intense engagement with city stakeholders, and takes into account the emerging digital technologies applied in cities that have been evolving the last 10 years (Fontanals I. & Vilatersana C., 2006). Thus, the activities has improved the quality of data collected, especially interdependences, which is one of the challenges presented in sections 4.4.1 and 4.4.2.

It is envisaged that this approach/analysis will bring new light to considerations of what the critical issues are in the three case study cities and highlight potential cascading effects that should ultimately lead to more sound management of the investigated water-cycle related hazards.

3.3 Assessing and visualising cascading effects in a holistic manner within HAZUR®

The "Interdependences" functionality within HAZUR® highlights the high degree of interconnectivity between services. Some of these connections are vital for the operation of a service, whereas other may be of lower significance. These interdependencies may well change with changing circumstances and are not always linear (so loops of interdependencies can rapidly form). HAZUR® allows for the visualisation of these interdependencies in a holistic way such as within a resilience map (Figure 33) or in a manner more akin to that of the physical based approach and see the interdependencies defined spatially using the GIS map functionality (Figure 34).

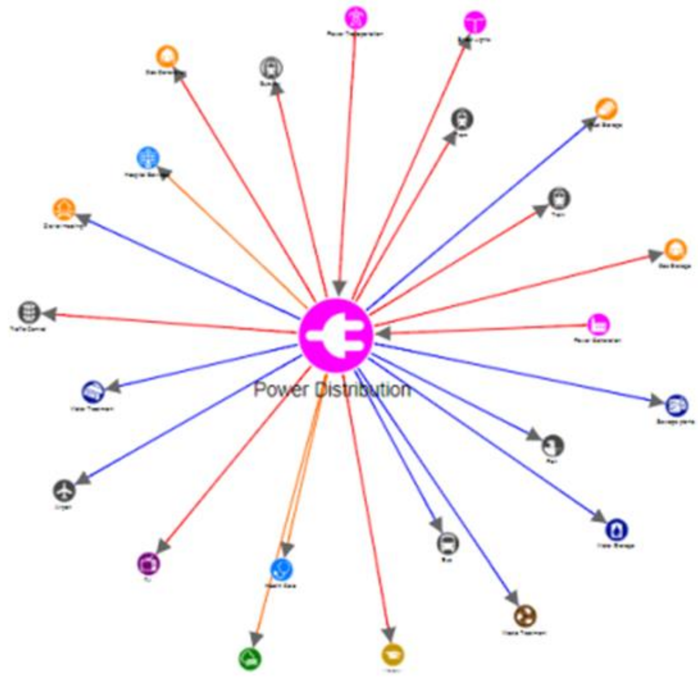

Figure 33 - Resilience map in HAZUR® tool, which shows the receiver and donor services from the Power Distribution service in a specific city case.

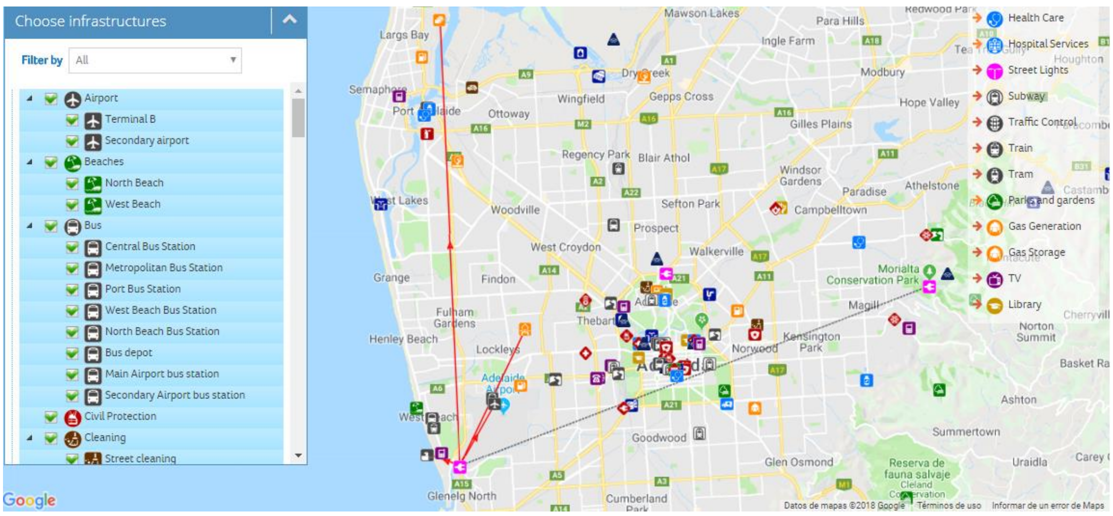

Figure 34 - GIS Map functionality in HAZUR® tool

As highlighted in previous sections, in order to understand the possible cascading effects it is important to keep into account the redundancies in place within infrastructures. The redundancies component is a significant feature of the HAZUR® tool with regards to the temporal processes of an impact and such data relating to redundancies can be captured and represented within the tool. Further information about the effect of impacts on services can be included within the “Responder” part of the tool. This component allows for the allocation of responders to a crisis can aid in the recovery time following an impact.

With the information about services and infrastructures captured it is possible to holistically simulate impacts and cascading failures from differing scenarios. These scenarios can be simulated using physical based modelling results as drivers/inputs.

3.3.1 Bridging the gap between Holistic and Physical based modelling

To understand and foresee the cascading failures in a city, it is necessary to understand the direct effects of impacts on services and infrastructures. Once details such as interdependencies, redundancies, responders and additional information, relating to the infrastructures and services have been captured the link/bridge between physical model outputs and the holistic modelling can be achieved through the "What If" analysis. In this approach, based on outputs from the physical modelling, the user can input into HAZUR® what infrastructures and consequently services have been impacted and taken offline (information provided by physical models).

A cascading effect visualisation module allowing selecting the different steps of cascading effects is under study, thus allowing a clearer analysis of the cascading effects. Secondly, the MANAGER module includes a simulation functionality; it allows to model a concrete impact by showing the state of the city, i.e. evolution in time of state of services (or infrastructures if descending at the infrastructure level) both in a Gantt diagram and a graph (Figure 37).

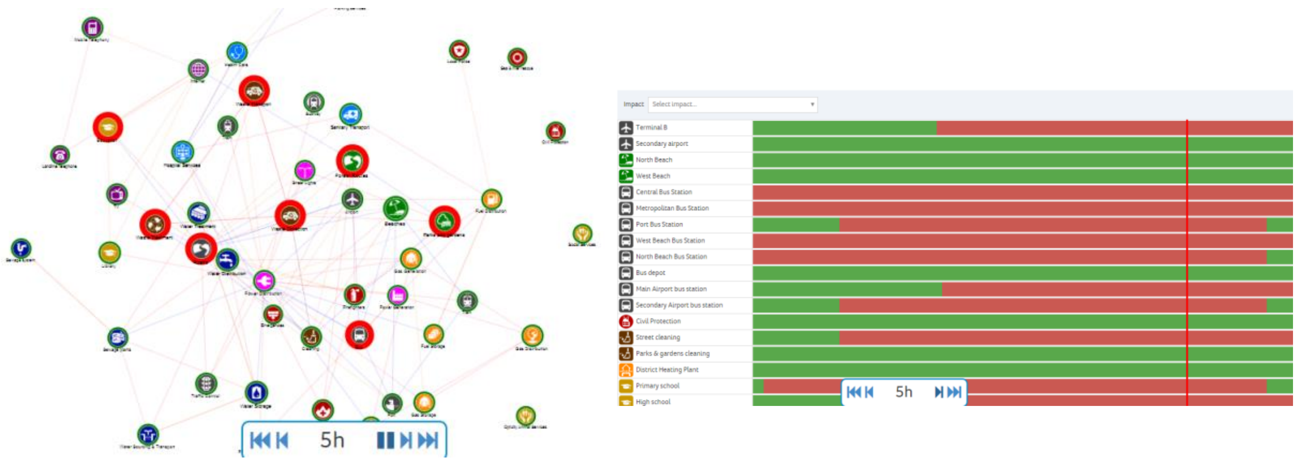

Figure 35 Visualisation of affected urban services due to cascading failures (conceptual & Gantt diagram).

Moreover, the simulation module allows to visualise different scenarios (i.e. different cascading failures simulations depending on the responder used), which is useful not only for forensic purposes, but also for prevention. These different scenarios may take into account information from other sources (i.e. output of other sources, sectorial models, etc.).

Simulation functionalities may also be used to engage city stakeholders in urban resilience. For instance, it is useful to choose specific scenarios where the interdependencies between services and infrastructures can create cascading effects of concern. This process will help to offer further focused areas where multiple stakeholders can come together to address practical concerns in a collaborative manner without raising concerns of overlaps, inefficiencies, data management, or over-burdening resources. In addition results from the simulations within HAZUR® may reveal infrastructure and services failures not previously captured in the initial physical modelling step.

Knowledge gained through the holistic analysis within the HAZUR® tool can be fed back into the physical modelling process in a cyclic approach (as highlighted earlier in Figure 32) to get more detail insights into the impacts that may result from cascading failures and means in which to improve the cities resilience against such failures.

In conclusion, HAZUR® allows a holistic analysis of cascading failures in urban services by visualising cascading effects beyond sectorial models and serves as a powerful means of both engaging stakeholders and improving physical models.

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5 Annex

5.1 Historical Incidences of cascading service failures

5.1.1 Historical incidences of cascading effects in Bristol

Tidal flood events pose significant risks to the city of Bristol due to the city's proximity to the Bristol Channel. In 1981 tidal flooding event lead to flooding of properties, in January 2014 tidal flooding during rush hour lead impediment of traffic flow along the Portway (one of the major traffic routes through the city), and more recently in January 2018 there were impacts on local businesses as a result of water damage from a tidal flooding event.

In addition to tidal flooding, pluvial flooding also poses significant risks/concerns to the city. On July 10th 1968 rainfall and fluvial flooding combined with a high tide made roads impassable. Flooding affected local businesses such as loss of stock due to flood damage within Will's Tobacco factory and flood depths in excess of 1.5m in some areas lead to power cuts and contaminated waters from combined sewer surcharge, CSO spills and foul water in watercourses flowed overland.

Severe rainfall on November 21st 2012 caused significant flooding and travel disruption throughout the city (Figure 36). Roads affected include Stanton Road, where people could not access or exit their properties without passing through floodwaters. At Whitchurch Lane manhole covers were surcharging due to pressures on the drainage system.

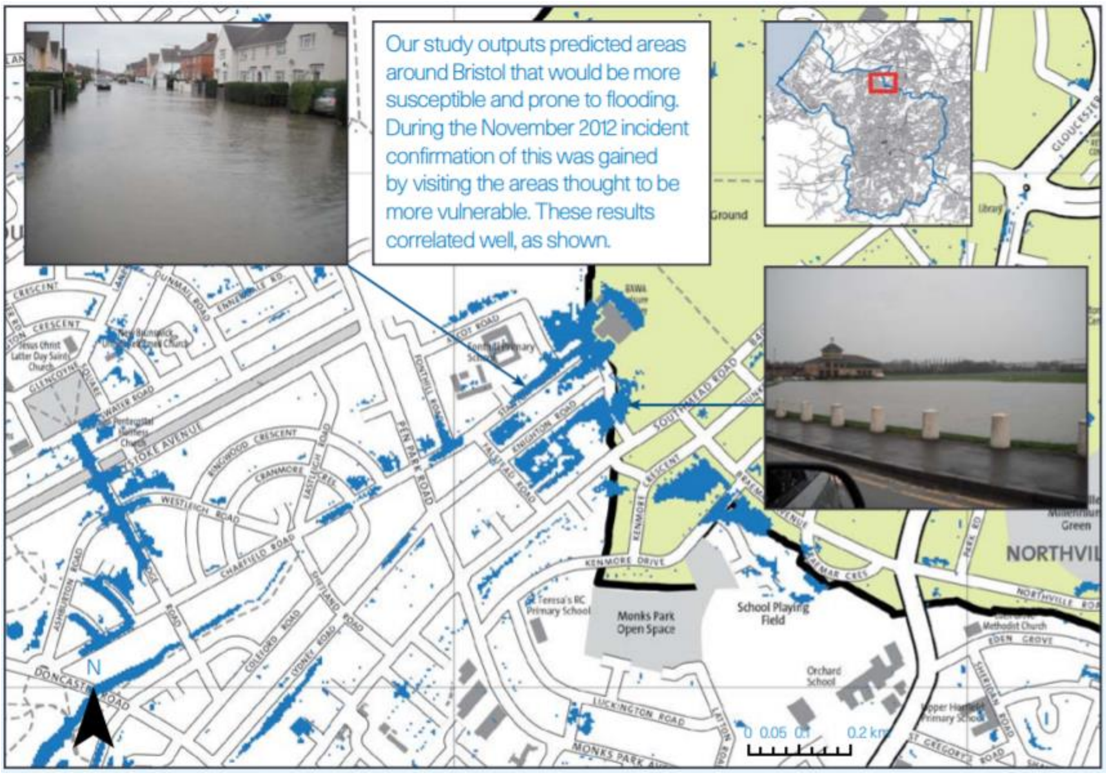

Figure 36 - Evidence verification of flood model predictions against November 2012 floods (Flood Risk and Asset Management Team, 2018)

Whitchurch Lane was affected again in November 2016 whereby several cars were impacted by floodwaters. With the locations and timing of this flooding event coinciding with bin collection day waste removal services within the area were also impeded Areas adjoining Greenfield land were particularly vulnerable due to prolonged rainfall leading up to the larger downpours that had raised water table levels. This particular rainfall event was of great significance in that it was noted as being the most rainfall in a year in the UK on record.

The roads flooded in all of the above scenarios could have affected critical emergency service routes and in some cases the fast flowing flood waters caused damage to the roads surfaces which later required repair.

5.1.2 Historical incidences of cascading effects in Barcelona

Urban resilience planning in the city of Barcelona has been evolving over a long period of time in a number of stages, some of which were not specifically intended to address this issue as such. As progress was made in this area, management and operational processes started to address vulnerabilities, adjust operating procedures and protocols and increasingly ensure that critical situations were tackled from a holistic point of view. This is the result of considering urban processes and systems that are increasingly complex and interdependent. In this evolving process, there have been three distinct stages:

During the first stage, up to 2009, plans and projects to generate resilience in the city were developed corresponding to a particular area and resolving specific problems, but no permanent cross-sector co-ordination mechanisms or methods were put in place that would facilitate their integration into the interdependent processes of other areas, or the coordinated incorporation of all the internal and external players. Gradually, plans, projects and actions were implemented in the city aimed at reducing vulnerability, configuring increasingly consistent scenarios, ready to tackle critical situations in the city.

Regarding this first stage, since 1997, Barcelona has implemented a drainage plan to minimise the impact of critical situations caused by floods, and by rainwater and sewage pouring into the sea during the torrential downpours that are typical of the Mediterranean climate, events that increase their impact due to the highly impervious layout of the city. These critical episodes were common before this plan was developed. The creation of a network of 13 laminated underground tanks built to hold the rainwater and then send it to the two purification plants, operated remotely and managed according to the weather and the state of the network, has effectively dealt with this issue and, as well as minimising flood damage, has ensured the coastal and beach waters are of exceptional quality.

A special achievement aimed to manage critical situations was the creation of the Municipal Emergency Plans, establishing protocols and response systems for the city in relation to known, possibly recurring risks and potentially hazardous exceptional situations. Barcelona currently has the Municipal Civil Protection Plan, which also incorporates action plans for heat waves, strong winds, and rough seas, and up to 12 Municipal Emergency Action Plans (PAEM) and Specific Municipal Emergency Plans (PEEM) for tackling particular impacts such as floods, forest fires or power, water or gas shortages, among other things. Another project involved the deployment of the joint command room, which, since 2005, has been co-ordinating all the reactive interventions carried out by the Guàrdia Urbana (city police), the Mossos d'Esquadra (regional police), the fire service and the Medical Emergency Services. When it was first created, it was the only one of its kind in Europe; it ensures fast reaction times and the rational use of resources. This command room also serves as a base for the Link and Co-ordination Centre (CECOR), a meeting place for the different services involved when municipal emergency plans are activated.

Despite the real value generated by all these plans and projects, during the first part of the last decade, there were a series of critical situations, mainly in the area of infrastructures and services, which made the city aware of the need for a paradigm shift to reduce vulnerability, ensure an effective response to these situations and restore all the services affected by the crisis as quickly as possible. The most critical situations that occurred during this period and their causes are described briefly below:

- In January 2005, the collapse of the tunnel being constructed to extend metro line 5 to the Carmel neighbourhood led to the evacuation of residents from 54 buildings.

More than 1000 people were affected and four buildings had to be demolished (Figure 37).

Figure 37 - Aerial overview of the buildings affected by the tunnel collapse in 2005.

- In June 2007, a stretch of the container wall surrounding the future underground car park, on the site of the former Bayer building, collapsed, on the corner between Calabria St. and Paris St. The collapse of this wall led to the destruction of part of the road and bus lane, a high voltage electricity line and a gas pipeline, and the sparks caused a fire, which lasted for several hours.

- In July 2007, a high voltage electricity wire fell on a transformer in the Collblanc substation, causing a short-circuit that affected the entire network, eventually leading to a fire in the Maragall substation (Figure 38) that affected 323,337 users for 56 hours and 42 minutes. The critical nature of the electricity network, particularly due to it being in an urban environment, meant a number of services dependent on electricity were affected, and generators needed to be used to provide a provisional power supply in the affected areas.

Figure 38 - . Electrical fire at Maragall substation.

The uncertainty about the real vulnerability of infrastructures, the risk of suffering another critical interruption to public services of this magnitude and the high probability of a knock-on effect on all other basic services, alerted the municipal government to the need for a new paradigm. Specifically, the power cut impacted a series of basic services and this had a very negative impact on the living conditions of the local residents affected, the possible preventive solutions were not immediate, and they did not only depend on the municipal government.

This is when the second stage of the resilience process in Barcelona began. It was at this point that cross-sector collaboration with both internal, external players being identified as a key objective and it was decided that the proposals should be holistic in their approach. At this time, the focus shifted to infrastructures and services, the key protagonists in the critical situations experienced in the city. The main steps taken during this stage were as follows:

- A diagnosis of the situation, with the aim of identifying any weak points and interdependencies, and the basic operating procedures for the city's essential services, was carried out in 2008 in a project called Security in Service Provision (3Ss in Catalan). Participating in the process were the city's main service providers and technical teams from the various related municipal areas (Figure 39).

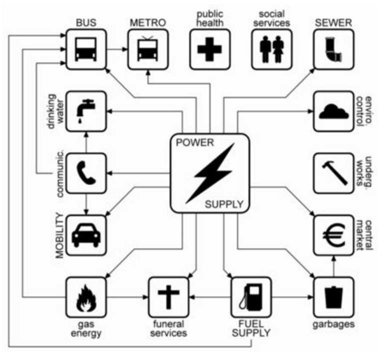

Figure 39 - Interdependences between power supply and urban services developed in the framework of the 3Ss Project.

- We then moved on to the operating phase in which resilience is generated for the city. Charged with developing resilience projects, aimed at minimising or eliminating (where possible) the risks detected, using a cross-sector, collaborative approach involving all the different players, the Infrastructure and Urban Services Committees (TISU) were set up, with 8 working groups from the different infrastructures and service areas. A working method was also established that guaranteed the continuity of the process and the on-going updating of the risks addressed. These committees evolved into the Barcelona Urban Resilience Boards (TdR), leading to a reorganisation of the working groups and making improvements in the methods. Several existing groups were reinforced and “Assistance to People and Urban Planning” boards were created.

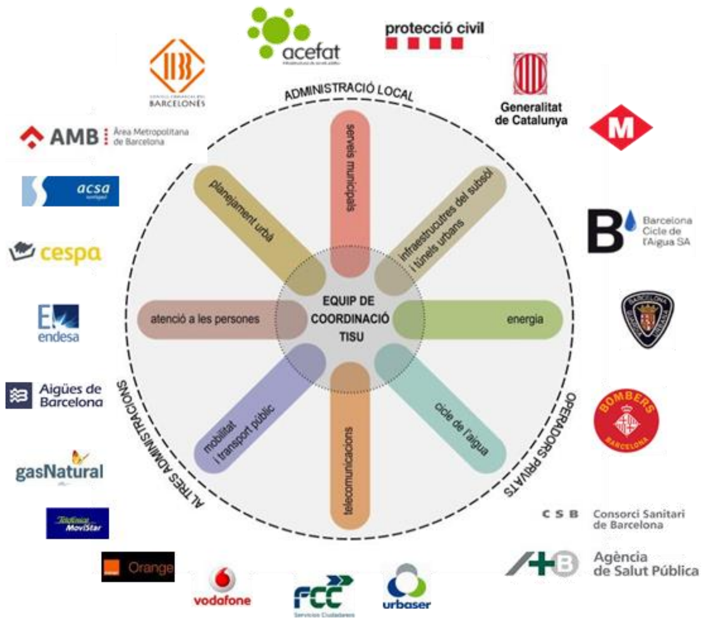

Figure 40 - Resilience boards working groups and stakeholders involved.

The implementation of the TdR projects led to the improvement of the capacity of the city to tackle with critical situations, even when, shocks are unpredictable and turned to hit the city again:

- In the winter of 2012, while provisional works on the electric grid were done in a trench at the Poblenou neighbourhood, a gas leak was found by the workers. After digging out the trench the gas company located the leakage and repaired it with a temporal solution. Two days later, due to the works done, a water pipe line buried below the gas pipe broke down, disrupting the water service and flooding the trench and affecting the temporal reparation of the gas pipe which became filled with water for more than 17 km. The electrical supply was subsequently cut off to minimize the risk although the grid was not affected. The effects of these cascading failures are reflected by the 4000 gas clients without service affected during 6 days in a winter cold wave, 400 houses, public buildings, companies, etc. affected during 12 hours of electrical cut off and 217 clients affected by water disruptions for more than 24 hours.

- On 24 November 2016 a tension fall of the electrical network caused the failure of a pumping station (part of the water supply network), and as a consequence of this, the flow of water stopped immediately causing a water hammer effect inside a half metre of diameter pipe. The strong impact broke the pipe causing a water leak that, apart from leaving without supply of water to 10,000 users, collapsed the road and for more than two hours one of the main arteries of the city, the mobility and the transport service was affected causing six traffic jams kilometres in length (Figure 41). One of the users affected by the water shortage was found to be Vall d'Hebron hospital, one of the most important hospitals of the city, which had to suspend surgical interventions and divert the service of emergencies to other hospitals within the city because the ambulances could not access to the hospital. It took three hours for the water supply to be re-established.

Figure 41 - Highway flooded by the water pipe burst in 2016.

Those events again were used to put in practice as the lessons learned in the past and the performance of the real needs, the continuous improvement and actualisation of the procedures required to reduce vulnerabilities and the redefinition of the urban systems according to the changing urban environment. To address these aims, the protocol between service supply companies and emergency services or the telecommunication protocol are revised periodically, and the optimisation of the sub-soil auscultation protocol to control and prevent affectations between the different services infrastructures.

Since the new municipal government has come to power, a need has been identified to reinforce and prioritise resilience projects that target the most vulnerable citizens and groups and to incorporate citizen participation in projects that are enriched and improved through collaboration with citizens. This new (third) stage will entail a strongly operational approach, guaranteeing the creation of real value for the city, accompanied by sound strategic planning, in keeping with key international perspectives and requirements. In this new phase, a database of the critical assets within the city boundaries is being developed to improve the communication among municipal equipment's sorting by their relevance for the city normal operation and under crisis events, identifying and establishing the interdependencies between urban assets, services, emergency response and attendance to the population.

5.1.3 Historical incidences of cascading effects in Lisbon

Lisbon has records of several meteorological events resulting in occurrence of failure of services resulting in cascading events to other services or activities in the city. In this section, an overview of relevant events is given, taking into consideration the interdependencies identified in D2.1 and the RESCCUE services covered.

In Lisbon, relevant hazards identified include flooding, windstorms, storm surges and heat waves. In the following tables, a selection of observed historical events with cascading failures is given.

In the case of rainfall induced events, urban flooding is a frequent event in Lisbon and one of the most relevant ones for the RESCCUE sectors. In Table 10 selected events are listed, together with the corresponding estimated rainfall return period. Given the spatial variation of rainfall, limited number of existing reference rain gauges and other factors relevant for flooding risk, often the estimated return period for rainfall intensity is not a good explanatory factor for the magnitude of the observed flooding. The events reported in Table 10 correspond to important flooding situations even if the return period calculated from existing data is low.

Table 6 – Selected flooding events in the last decades with estimated rainfall return period

Decade	T= 500 y	T= 100 y	T= 50 y	T= 20 y	T= 10 y	T = 5 y	T= 2 y
1960		26-11-1967					
1970					25-09-1976 10-02-1979	09-10-1978	17-10-1973 11-11-1975 30-08-1976 05-11-1977 26-12-1978
1980	19-11-1983	08-11-1983		26-11-1985	27-12-1981 28-08-1987	13-04-1982 27-10-1983 11-11-1985 15-09-1986 27-05-1989	25-09-1981 03-02-1982 16-11-1983 03-11-1984 11-11-1986 09-01-1987 24-02-1987 13-10-1988
1990		18-10-1997 02-11-1997		12-05-1993 27-07-1999 20-10-1999	24-11-1997	30-04-1990 18-10-1990 07-11-1990 12-02-1991 31-10-1993 01-11-1993 08-11-1994 25-12-1995 18-05-1997	13-10-1990 12-02-1991 17-04-1991 14-11-1995 31-12-1995 08-01-1996 20-12-1996 18-10-1997 31-05-1998 01-05-1999 07-08-1999 20-10-1999
2000				24-12-2002 18-02-2008	18-10-2008	06-02-2001 28-20-2001 30-09-2007	22-11-2000 23-01-2002 01-10-2003 29-01-2004 10-10-2005 21-09-2006 22-10-2006 25-10-2006 03-01-2008
2010			29-10-2010	13-10-2014	26-11-2014		21-04-2011 16-05-2011 28-05-2011 02-11-2011 23-09-2012 21-03-2013 17-01-2014 22-09-2014 11-11-2014 19-11-2014 15-04-2015 26-10-2015 04-11-2016

Other events associated with hazards relevant to Lisbon are also referred in this section including tables for the sectors and services considered in RESCCUE for Lisbon.

Intense rainfall combined with local infrastructure characteristics result in insufficient conveyance capacity of drainage systems (both surface and underground), thus generating high overland flows reflected in high water levels and flow velocities. The main effects of the overland flow are in **transport and mobility** and illustrated in Table 7.

Table 7 - Cascading effects of drainage system failures in other services and activities due to flooding and high estuary water level in Lisbon: transport and mobility

<table>
<tr><td colspan="2">Transport and mobility
Flooding of roads, damages in infrastructures, traffic disturbance and interruptions, flooding of underground infrastructures (metro, train, and parking), interruption of public transport, damage to vehicles.</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Damaged pavements, 2008-02-18
(Alcântara catchment, Maria do Céu Almeida)</td><td>Flooded road tunel, 2008-02-18
(Campo Grande, Maria do Céu Almeida)</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Lisbon downtown, 2014-10-13
(Rua das Pretas, Ana Machado Brissos, sicnoticias.sapo.pt/pais/2014-10-13-Inundacoes-na-Grande-Lisboa)</td><td>Lisbon downtown, 2014-10-13
(Praça da Figueira, João Fernandes, sicnoticias.sapo.pt/pais/2014-10-13-Inundacoes-na-Grande-Lisboa)</td></tr>
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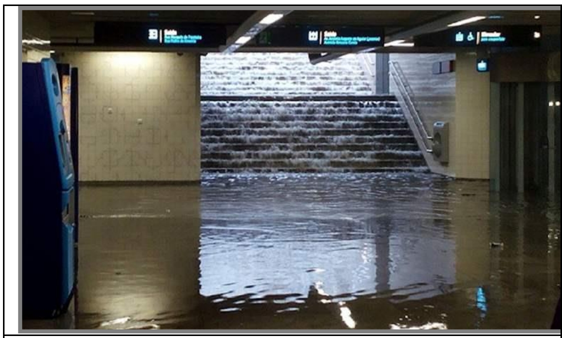	
São Sebastião Metro entrance, 2014-10-13 (CML)	Rossio, 2014-10-13 (CML)
	
Belém Tower entrance flooded by high estuary water level, 2016-05-07 (CML)	Belém Tower entrance flooded by high estuary water level, 2016-05-07 (CML)

Regarding **wastes**, the cascading effect from failures in the drainage system causes disruptions in waste collection components and the spilled wastes can in turn contribute to increase obstructions of drainage components (Table 8). Since use of mechanism to avoid movement of containers is almost generalised, these problems are limited today. Additionally, dragging of wastes and debris requires clean-up operation before resuming service in roads.

Table 8 - Cascading effects of drainage system failures in other services and activities due to flooding and high estuary water level in Lisbon: wastes

Wastes Flooding causing containers overturn, dragging, floating, filled with water and damage. Overland flows can result in spread of wastes on streets, blockages of inlets and other drainage components. Accumulation of debris on streets requiring deep cleaning before resuming service.	
	
Floating containers in high flooding water (CML)	Debris dragged by overland flow in road (CML)
	
Lisbon cleaning operations after flooding (CML)	

The **wastewater system infrastructures**, namely pumping stations and wastewater treatment plants, can have cascading effects from failures in the drainage system causing disruptions in these components functions and secondary effects for instance in Tagus river due to discharge of wastewater with lower levels of treatment than desired. Table 9 shows examples of such failures in infrastructures.

Table 9 - Cascading effects of drainage system failures in other services and activities due to flooding and high estuary water level in Lisbon: pumping stations and wastewater treatment plants

Wastewater system infrastructures Flooding of pumping systems or treatment plants can result in electrical or mechanical failures with consequences in terms of pumping lower capacity and combined sewer overflows (CSO) or, in the worst case, causing reduction of treatment efficiency or interruption of treatment processes.	
	
Alcântara WWTP flooding (Águas do Tejo Atlântico)	System failure due to flooding in Alcântara WWTP (Águas do Tejo Atlântico)
	
Flooding in the pumping station entrance (Águas do Tejo Atlântico)	Water entering in the pumping station (Águas do Tejo Atlântico)

The occurrence of high water level in the Tagus estuary, due to tides, storm surge or mean sea level rise, can result in entrance of high salinity water in the drainage system. This can cause reduction of treatment efficiency with effects in Tagus River due to discharge of wastewater with lower levels of treatment than desired, or even flooding when the mean sea level rise is combined with extreme precipitation events.

Table 10 - Cascading effects of drainage system failures in other services and activities due to flooding and high estuary water level in Lisbon: weirs and drainage system

Wastewater drainage system Entrance of high salinity water in the drainage system, causing reduction of treatment efficiency with effects in Tagus river due to discharge of wastewater with lower levels of treatment than desired. Occurrence of flooding, when the mean sea level rise is combined with extreme precipitation events and the drainage system capacity is exceeded, with consequences in the drainage system and in the treatment process.	
	
Sea water entrance in the crest level of a weir (Águas do Tejo Atlântico)	Sea water entrance through a valve (Águas do Tejo Atlântico)
	
Drainage system capacity exceeded when sea level rise and precipitation event combined (22-09-2014) (Águas do Tejo Atlântico)	

The **electrical energy supply infrastructure**, namely underground primary and secondary substations, are susceptible to damage where failures in the drainage system occur. Disruptions in component, such as transformers and electric buses might have secondary effects for instance in other essential services.

Due to failures from the electrical energy supply caused by flooding, some urban services could be affected, such as street lighting, traffic lights, some telecommunications that depend directly to the distribution grid and other consumers.

After the floods that affected the substation of Praça da Figueira (2003) and the secondary substation of Rossio, it was necessary to implement some measures. In the case of substation of Praça da Figueira it was built with a fence surrounding the ventilation surface openings, as shown in Table 11. By adding a fence, it helps preventing similar floods, or at least containing floods with a lower water level than the flood of 2003. In addition, in Praça da Figueira, an extra water extraction pump was installed, to achieve better levels of reliability and more resilience to facing future similar flooding events. Table 11, shows evidences of the water level inside each substation. Water marks on the walls of both substations reveals the water level reached during flooding, and at this level equipment's inside each substation were affected.

Table 11 - Cascading effects of drainage system failures in other services and activities due to flooding and high estuary water level in Lisbon: electrical energy supply

Electrical energy supply Failure energy supply, failure electrical equipment's, flooding in underground substations and secondary substations. In case of flooding in telecommunication infrastructure, that may affect the telecommunication service, the energy supply operation could be impacted, mainly on SCADA systems disturbance.	
	
Typical flooding situation at Rossio (2014-10-13, CML)	Flooding level at secondary substation (Rossio, Maria do Céu Almeida)
	
Flooding level at secondary substation (Rossio, Maria do Céu Almeida)	Water extraction pumps (Secondary substation in Rossio, Maria do Céu Almeida)

	
Typical flooding situation at Praça da Figueira, 2014-10-13 (Praça da Figueira, João Fernandes, sicnoticias.sapo.pt/pais/2014-10-13-Inundacoes-na-Grande-Lisboa)	Surface openings (without fencing back in 2003-08-31) (Praça da Figueira, Maria do Céu Almeida)
	
Water level reached in flooding event in 2003-08-31 (Substation Praça da Figueira, Maria do Céu Almeida)	Transformer room and water level (Substation Praça da Figueira, Maria do Céu Almeida)
	
Fence (Substation Praça da Figueira, Maria do Céu Almeida)	Water extraction pumps (Substation Praça da Figueira, Maria do Céu Almeida)

In addition to flooding events, strong winds have also posed problems for the city of Lisbon in the past. The action of strong winds or windstorms causes a significant number of drops of branches and tree in Lisbon streets. According to Ribeiro (2011), around 16% of the events causes consequences to vehicles. Some of the impacts of such events are depicted in Table 12 and Table 13.

Table 12 - Cascading effects of green infrastructures failures in other services and activities due to windstorms in Lisbon

<table>
<tr><td colspan="2">Green infrastructures
Collapse of trees or tree branches due to strong winds. Cascading effects on urban drainage due to obstruction of components and surface flows. Cascading effects on transport system, causing road and rail traffic disturbance and interruptions.
Cascading effects on electrical energy supply or communications components, causing damage to equipment and lines, are not likely in Lisbon.</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Several hundred broken tree branches in Lisbon, 11-12-2017
(www.dn.pt/sociedade/interior/mau-tempo-centenas-de-quedas-de-arvores-e-estruturas-no-porto-e-em-lisboa-8976176.html)</td><td>Several hundred broken tree branches in Lisbon, 11-12-2017
(www.dn.pt/sociedade/interior/mau-tempo-centenas-de-quedas-de-arvores-e-estruturas-no-porto-e-em-lisboa-8976176.html)</td></tr>
</table>

Table 13 - Cascading effects of urban equipment failures in other services and activities due to flooding and windstorms in Lisbon

<table>
<tr><td colspan="2"><u>Urban equipment</u>
Damaged urban equipment can cause the following cascading effects:
on urban drainage, causing obstruction of components (inlets, trenches, sewers, etc.).
on transport infrastructure, causing road and rail traffic disturbance and interruptions.
Windstorms damages to signs and traffic lighting can impact traffic in the streets.</td></tr>
<tr><td></td><td>
</td></tr>
<tr><td>Collapse of urban equipment
(CML)</td><td>Collapse of urban equipment
(SiC Notícias)</td></tr>
</table>

5.2 Glossary of terms

Various terms are used within this document that can vary within differing literature but within the context of this document they will be defined as follows.

Accommodation approach: The accommodate approach involves the continued occupancy and use of vulnerable zones by increasing society's ability to cope with the effects of extreme events. (source: Linham M. M. and Nicholls R. J. 2010)

Actor: A person linked to a specific action within the resilience action, but who does not participate in the resilience implementation process. (source: HAZUR® terminology)

Adaptation (to climate change): The process of adjustment to actual or expected climate, and its effects. See also Autonomous Adaptation, Evolutionary Adaptation, Incremental Adaptation and Transformative Adaptation. (source: IPCC 2014a)

Adaptation assessment: The practice of identifying options to adapt to climate change and evaluating them, in terms of criteria such as availability, (co-) benefits, costs, effectiveness, efficiency and feasibility. (source: adapted from IPCC 2014a)

Adaptation measures: are specific interventions to address a specific climate risk. This can be a measure that for example

- Prevents a hazardous event from happening
- Reduces or deflects the impact of a hazardous event
- Improves recovery after a hazardous event has happened

Measures can be technical, infrastructural, but also legal, economical of social. So a measure could be building a dam, increasing the price of drinking water or raising awareness of flood risks. (Rocha et al., 2017)

Adaptation Options: The array of strategies and measures that are available and appropriate for addressing adaptation needs. They include a wide range of actions that can be categorized as structural, institutional, or social. (source: IPCC 2014a)

Adaptation strategies: are a collection of measures linked to specific risks and their impacts. The strategy provides a framework of which the measures are the practical outcome. A strategy consists of:

- Identification of the risks and their impacts
- Strategic goals that need to be achieved
- Measures that help achieve those goals by addressing the risks
- Implementation plan for the measures

The analysis in this phase will be based on the individual measures, but the outcome will be beneficial in developing the strategies. (Rocha et al., 2017)

Adaptive capacity (or adaptability): The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. (source: IPCC 2014a)

Business Interruption: it relates to the monetary losses a business suffers as an indirect result of an impact. E.g. flooding of fabrication plant that is flooded is considered direct damage, but the reduction in the purchases of inputs, which will affect a supplier of the fabrication plant, is considered an indirect damage and as such Business Interruption.

Cascading Effects: A sequence of events in which each one produces the circumstances necessary for the initiation of the next. See also Consequence Analysis (source Allaby 2004). Or a sequence of events in which each individual event is the cause of the following event; all the events can be traced back to one and the same initial event. (source: Rome *et al.* 2015)

Climate: Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. (source: IPCC 2013)

Climate Change: Climate change refers to a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. (source: IPCC 2013)

Climate Projection: A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. (source: IPCC 2013)

Climate Model: A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for some of its known properties.(source: IPCC 2013)

Climate System: The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. (source: IPCC 2013)

Co-benefits: The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefit. (source: Allaby 2004)

Consequence: The outcome of an event affecting objectives. (source: ISO/IEC 27000: 2014 and ISO 310000: 2009)

Consequence Analysis: Consequence Analysis is estimation of the effect of potential hazardous events. (source: Australian Emergency Management Glossary (1998))

Contextual Vulnerability: A present inability to cope with external pressures or changes, such as changing climate conditions. Contextual vulnerability is a characteristic of social and ecological systems generated by multiple factors and processes. (source: IPCC 2014a)

Coping Capacity: The ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term. (source: IPCC 2014a)

Further definition: The ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters. (Source: UNISDR 2009)

Critical Infrastructure (CI): An asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions. Organizations and facilities that are essential for the functioning of society and the economy as a whole. (source: European Commission: Council Directive 2008/114/EC ISO/IEC TR 27019:2013)

Critical Infrastructure (CI) Dependency: CI dependency is the relationship between two (critical infrastructure) products or services in which one product or service is required for the generation of the other product or service. (source: Rome et al 2015)

Critical Infrastructure (CI) Element: Part of a CI. It can have sub-elements. (source: Rome et al 2015)

Critical Information Infrastructure (CII): Critical information infrastructures ('CII') should be understood as referring to those interconnected information systems and networks, the disruption or destruction of which would have serious impact on the health, safety, security, or economic wellbeing of citizens, or on the effective functioning of government or the economy. (source: OECD Recommendation of the Council on the Protection of Critical Information Infrastructures C(2008)35)

Critical Infrastructure (CI) Interdependency: The mutual dependency of products or services. (Source: ACIP 2003)

Critical Infrastructure Protection (CIP): All activities aimed at ensuring the functionality, continuity and integrity of critical infrastructures in order to deter, mitigate and neutralise a threat, risk or vulnerability. (source: EC Council Directive 2008/114/EC)

Critical Infrastructure (CI) Sector: Economic sectors considered critical. (source: Rome et al 2015)

Damage classification: Damage classification is the evaluation and recording of damage to structures, facilities, or objects according to three (or more) categories. (source: UN Department of Humanitarian Affairs, 1992)

Decision: The result of making up one's mind regarding a choice between alternatives (source: Wijnmalen et al 2015)

Decision Support: The structure process of activities that support decision makers and other stakeholders in coping with and resolving problems they are faced with. (source: Wijnmalen et al 2015)

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: it 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).

Disruption: Incident, whether anticipated (e.g. hurricane) or unanticipated (e.g. a blackout or earthquake) which disrupts the normal course of operations at an organization location. (Source: ISO/PAS 22399, 2007)

Drivers: Drivers are aspects which change a given system. They can be short term, but are mainly long term. Changes in both the climate system and socioeconomic processes including adaptation and mitigation are drivers of hazards, exposure, and vulnerability. Drivers can, thus, be climatic or non-climatic. Climatic drivers include: warming trend, drying trend, extreme temperature, extreme precipitation, precipitation, snow cover, damaging cyclone, sea level, ocean acidification, and carbon dioxide fertilisation. Non-climatic drivers include land use change, migration, population and demographic change, economic development. (source: based on IPCC 2014b (SPM))

Efficiency: The good use of time and energy in a way that does not waste any. (source: http://dictionary.ca mbridge.org/dictionary/english/efficiency)

Effectiveness: The ability to be successful and produce the intended results (source: http://dictionary.ca mbridge.org/dictionary/english/effectiveness)

Ensemble: A collection of model simulations characterizing a climate prediction or [climate] projection. (source: IPCC 2013)

European Critical Infrastructure: Critical infrastructure located in Member States the disruption or destruction of which would have a significant impact on at least two Member States. The significance of the impact shall be assessed in terms of cross-cutting criteria. This includes effects resulting from cross-sector dependencies on other types of infrastructure. (source: Council Directive 2008/114/EC)

Event: Occurrence or change of a particular set of circumstances. An event can be one or more occurrences, and can have several causes. An event can consist of something not happening. An event can sometimes be referred to as an "incident" or "accident". (source: ISO/PAS 22399:2007 and ISO/IEC 27000:2014)

Evolutionary Adaptation: For a population or species, change in functional characteristics as a result of selection acting on heritable traits. The rate of evolutionary adaptation depends on factors such as the strength of selection, generation turnover time, and degree of outcrossing (as opposed to inbreeding). (source: IPCC 2014a)

Exposure: The presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected (source: IPCC 2014a)

Extreme Weather Event: An extreme weather event is an event that is rare at a particular place and time of year. (source: IPCC 2013)

Flood Risk: The risk associated with flood events in a certain region and in a certain time period.

Green Infrastructure: Broadly defined as a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings. Note: Green infrastructure may incorporate both landscape and water features, the latter of which may be termed 'blue infrastructure'. Other terms include 'green-blue infrastructure' and 'green and blue infrastructure'. (Source: European Commission 2013)

Grey Infrastructure: Familiar urban infrastructure such as roads, sewer systems and storm drains is known as 'grey infrastructure'. Such conventional infrastructure often uses engineered solutions typically designed for a single function. (source: Parliamentary Office of Science & Technology 2013)

Hazard: The potential occurrence of a natural or human-induced physical event or trend, or physical impact, 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. The term hazard usually refers to climate-related physical events or trends or their physical impacts. (source: IPCC 2014a)

Impact Chains: Impact chains permit the structuring of cause - effect relationships between drivers and/or inhibitors affecting the vulnerability of a system. Impact chains allow for a visualization of interrelations and feedbacks, help to identify the key impacts, on which level they occur and allow visualising which climate signals may lead to them. They further help to clarify and/or validate the objectives and the scope of the vulnerability assessment and are a useful tool to involve stakeholders. (BMZ 2014)

Impact: 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.

Improvement area: domain to be improved to increase the resilience of a specific urban area. For example: Improving the citizen service/Improving mobility in the coastal district of the city

Improvement project: specific action belonging to an improvement area that allows to reduce the recovery costs (political, economic, social, technological, environmental, and legal) in an urban area, thus increasing its resilience. For example: Setting up a free hotline for citizens/New roundabout in city access XY

Incident: Event that might be, or could lead to, an operational interruption, disruption, loss, emergency or crisis. (source: ISO/PAS 22399: 2007)

Incremental Adaptation: Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale. (source: IPCC 2014a)

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

Infrastructure: physical buildings and objects that provide or facilitate the distribution of a service. 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" an infrastructure could be a hospital, clinic, blood bank, etc.

Intangible damage: 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.

Intensity: The quality of being intense. The measurable amount of a property, such as force, brightness, or a magnetic field. (source: Oxford English Dictionaries https://en.oxforddictionaries.com/definition/intensity)

Interdependence: relationship between different services or infrastructures that is given when one service or infrastructure (donor) fails and makes fail another one (the receptor). [Example: waste water treatment plant X fails if Y power transformer fails.]. (source: Hazur® terminology)

Likelihood: The chance of a specific outcome occurring, where this might be estimated probabilistically. (source: IPCC 2014a)

Maladaptation: Actions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future. (source: IPCC 2014a)

Mitigation: The lessening of the potential adverse impacts of physical hazards (including those that are human-induced) through actions that reduce hazard, exposure, and vulnerability. (source: IPCC 2012)

Operators Group: Group formed by the steering group and the management of significant operators of infrastructure and services in the territory. (source: Hazur® terminology)

Passive Measure: It is a type of measure which does not use energy once it has been implemented. It is normally referred to adaptation measures for buildings indoor environments. (source: Van Hoof et al 2014)

Probability: Measure of the chance of occurrence expressed as a number between 0 and 1 where 0 is impossibility and 1 is absolute certainty. (Source: ISO Guide 73:2009). Or the likelihood of a specific outcome, measured by the ratio of specific outcomes to the total number of possible outcomes. Probability is expressed as a number between 0 and 1, with 0 indicating an impossible outcome and 1 indicating an outcome is certain. (source: Australian Emergency Management Glossary (1998))

Probabilistic Climate Projections: These are projections of future absolute climate that assign a probability level to different climate outcomes. This projection provides an absolute value for the future climate (as opposed to giving values that are relative to a baseline period) that assign a probability level to different climate outcomes. (source: Adapted from the UK Met Office 2014)

Protection approaches: A protection approach involves defensive measures and other activities to protect areas against flood risk. The measures may be drawn from an array of “hard” and “soft” structural solutions. (source: Linham M. M. and Nicholls R. J. 2010)

Player: A person linked to the management or the operation of a service or infrastructure in an urban area and engage in the resilience implementation process, including politicians, municipal technical staff and service operators. (source: Hazur® terminology)

Recovery: The restoration, and improvement where appropriate, of facilities, livelihoods and living conditions of disaster-affected communities, including efforts to reduce disaster risk factors. (source: UNISDR 2009)

Recovery time: it is Hazur® terminology and means the period of time during which an element (i.e. service or infrastructure) becomes inoperable or is not performing its proper function due to a certain impact (e.g. Flood, heat wave, drought or sea level rise)

Recovery time matrix: it is a matrix which gathers all recovery times of all services or infrastructures (i.e. rows) according to different impacts (i.e. columns). The rank of the matrix will depend on the services/infrastructures and impacts considered when developing the city model through Hazur®. This information is defined at the “what if” matrix of Hazur®

Redundancy: Service of infrastructure that can replace or can be replaced with another service or infrastructure. [Example: a power transformer able to replace another power transformer of the same urban area, a hospital that can accept people that cannot go to their district health center.]. (source: Hazur® terminology)

Reliability: Property of consistent intended behaviour and results. (source: ISO/IEC 27000:2014)

Resilience: The capacity of a social-ecological system to cope with a hazardous event or disturbance, responding or reorganizing in ways that maintain its essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation (Arctic Council, 2013) (source: IPCC 2014a)

Further definition: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions. (Source: UNISDR 2009)

Responder: Technical or human equipment to mobilize in case of crisis. [Example: a power generator, the police, a psychologist team.]. (source: Hazur® terminology)
Retreat approaches: In the measures context, the retreat approach refers to planned withdraw from the coast or the often inundated areas, rather than an unplanned or forced retreat which is also potentially possible in the face of sea level rise and climate change. (source: Linham M. M. and Nicholls R. J. 2010)

Risk: 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.

Scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g. rate of technological change, prices) and relationships. (source: IPCC 2013)

Sector: A part or division, as of a city or a national economy. (Source: American Heritage® Dictionary of the English Language)

Sensitivity: see **Susceptibility**

Service: Group of activities with the aim of meeting the needs and ensuring the quality of life of the inhabitants of a territory. (source: Hazur® terminology)

Social Infrastructure (Institutional): The social infrastructure includes the humans, organizations and governments that make decisions and form our economy as well as our institutions and policies. (source: Chappin and van der Lei 2014)

Social Infrastructure (Physical): Schools, hospitals, shopping or cultural facilities. (source: unpublished working glossary of UP KRITIS and BSI, 2014)

Source Control Measures: Source control measure means any stormwater management practice designed to reduce and/or slow the flow of stormwater into a combined sanitary and stormwater sewer or a separate stormwater sewer, including, but not limited to, any such practices commonly referred to as Low Impact Development or Best Management Practices. (source: New York City Administrative Code-Section 24-526. 1: Sustainable Stormwater Management)

Stakeholder: Person or organization that can affect, be affected by, or perceive themselves to be affected by a decision or activity. Note: A decision maker can be a stakeholder. (source: adapted from: ISO 31000:2009)

Steering Group: Group constituted almost entirely of senior administration officials with authority over essential services and infrastructure to ensure resilience in the territory being

studied. Responsible for defining the significant operators, territorial resilience objectives, the key processes, and to make major impacts that may occur. (source: Hazur® terminology)
Strategic Group: Group of senior political and managerial leadership of public organizations. It will bring conviction and political action to the project validating performances from a strategic standpoint. (source: Hazur® terminology)

Stressors: Events and trends, often not climate-related, that have an important effect on the system exposed and can increase climate related risk. (Source: adapted from Oppenheimer *et al.* 2014: p. 1048).

Susceptibility: (within RESCCUE susceptibility and sensitivity, will act as synonyms) 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 (Rocha et al., 2017).

Tangible damage: the monetary damage that has occurred as a result of an impact.

Transformative Adaptation: Adaptation that changes the fundamental attributes of a system in response to climate and its effects. (source: IPCC 2014a)

Uncertainty: A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. (source: IPCC 2014a)

Urban (Urban Area): Urban 'is a function of (1) sheer population size, (2) space (land area), (3) the ratio of population to space (density or concentration), and (4) economic and social organization.' (Source: Weeks 2010). Or the OECD-EU classification identifies functional urban areas beyond city boundaries, to reflect the economic geography of where people live and work. Defining urban areas as functional economic units can better guide the way national and city governments plan infrastructure, transportation, housing and schools, space for culture and recreation. (source: OECD 2012)

Urban Critical Infrastructure: An asset, system or part thereof located in an urban area which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in an urban area as a result of the failure to maintain those functions. (source: adapted from EC Council Directive 2008/114/EC)

Urban Critical Infrastructure System: Urban critical infrastructure from a systemic viewpoint. It is part of the urban system and simultaneously part of the national critical infrastructure system. (source: Rome et al 2015)

Urban System: System of urban areas (Urban settlements from a systemic viewpoint) (source: Rome et al 2015)

Vulnerability: 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 (Rocha et al., 2017).

Vulnerability Index: A metric characterizing the vulnerability of a system. A climate vulnerability index is typically derived by combining, with or without weighting, several indicators assumed to represent vulnerability. (source: IPCC 2014a)

Wicked Problem: A problem that is categorized by a great number of uncertainties. These include: on the stakeholders involved, the boundaries of the problem, long term organisational developments and responsibilities, amongst others. (Source: adapted from Wijnmalen et al 2015. Please also see Rittel and Webber 1973)