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# Deliverable 3.2: Tools with updated impact assessment models

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Document history

| DATE | VERSION | AUTHOR | COMMENTS |
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| | | | |
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| 18/07/2017 | 4 | B. Evans | Information from Barcelona's traffic model examined and incorporated into traffic modelling section |
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| 30/07/2018 | 13 | B. Evans | Minor amendments and corrections made based on EC review. |

1. **Changes with respect to the DoA**
   This deliverable has been considered as Confidential, whereas in the original DoA was considered Public. This change will be included in the next amendment of the GA, so the actual dissemination level is shown.

2. **Dissemination and uptake**
   Public.

**3. Short Summary of results (<250 words)**

Deliverable 3.2 – "Tools with updated impact assessment models" follows on from deliverable 3.1 "*Selection of methods for quantification of impacts of identified hazards"*. Based on novelties identified in Task 3.1, the existing tools developed on related projects by the RESCCUE project partners will be updated to include the latest methodologies. The document looks over means of quantifying impacts (both direct and indirect) on various infrastructure types and services including buildings, contents, vehicles, traffic and pedestrians. The methods/approaches used in numerous preceding projects including EU-Circle, CORFU, PEARL, and BINGO are highlighted and expanded upon where appropriate within the scope of planned work within this RESCCUE.

The impact assessments methods on multiple key services within each case study area have been defined. These include the use of updated depth-damage curves for Bristol, and means of updating depth-damage curves for Barcelona and Lisbon. This work will also involve adjustments that will be required to take into account the data requirements and needs of the several case study areas. Aquatec and Cetaqua have contributed to the definition of data requirements in this regard.

**4. Evidence of accomplishment**

This report provides a good basis and summary of methods being pursued within RESCCUE for the quantification of impacts on the major/critical services that constitute vital components in the smooth running of a city and therefore its level of resilience.

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# 1 Introduction

There has been numerous works in previous projects such as BINGO, CORFU, EU-Circle, PEARL, PREPARED, SAFE&SURE that have looked at resilience and the quantification of impacts on infrastructures. Where the predecessor to this document (Deliverable 3.1) looked at the methods used in quantifying impacts to critical infrastructures and services within a city, this document looks at the selected methods used specifically both within the aforementioned projects and within industry and examines how they will be utilised and expanded upon within the scope of RESCCUE project.

With overarching goals of RESCCUE to help cities understand and improve their resilience to climate change, this document looks to highlight the methods and tools to employed by RESCCUE within the case study areas to achieve this. Methods used and results obtained through analysis using these techniques will then be expanded upon later in the project when looking into the cascading effects.

# 2 Considered Hazards for Impact quantification

There are a multitude of hazards that can impact services and critical infrastructures within a city. Table 1 shows a list of hazards, and the services they can impact, that were highlighted in WP2, which had been identified as concerns by the three cities in the case study areas. In the framework of RESCCUE project, these natural hazards will be considered in the research sites and several novel and promising methodologies for the quantification of the related impacts will be explained in the following sections. These methodologies will be applied in the three RESCCUE research sites with different level of implementation and will allow detailed risk assessment considering direct and indirect impacts in the framework of Task 3.4 of WP3.

Table 1 – Services impacted by hazards

| Hazard | Potential impacted Services |
|---|---|
| Flooding (Pluvial, Fluvial, Storm Surge, Sea Level rise) | Energy<br>Transport<br>Waste<br>Water Cycle |
| Temperature (Heatwave, Drought) | Water Cycle |

# 3 Methodologies and tools for RESCCUE cities impacts assessment

## 3.1 Utilising indices to quantify impacts within the energy sector

Within the context of resilience, the electrical power system that is responsible for the supply of power to a city is regarded as being a critical infrastructure. Due to this fact, the power system has already been historically designed to be reliable and to be able to withstand certain unexpected outages by following the criterion of *N-k*, with *k* being equal to 1 or 2 in the current electrical grid (*N* refers to the number of elements in the grid and *k* refers to the element kept out of service). The *N-k* criterion means that the power system must be capable of operating normally even in the case of *k* component losses within the system. However, it is recognised that the system should be designed for even higher number of component losses due to the effects of climate change, which would challenge the system to withstand high-impact and low-probability (HILP) events as a result of extreme weather scenarios. Such scenarios may lead to cascade outages or parallel failures which implies a loss of any existing resilience. The power grid resilience can be understood as the capacity of the network to absorb, adapt and recover from extreme events (Figure 1).

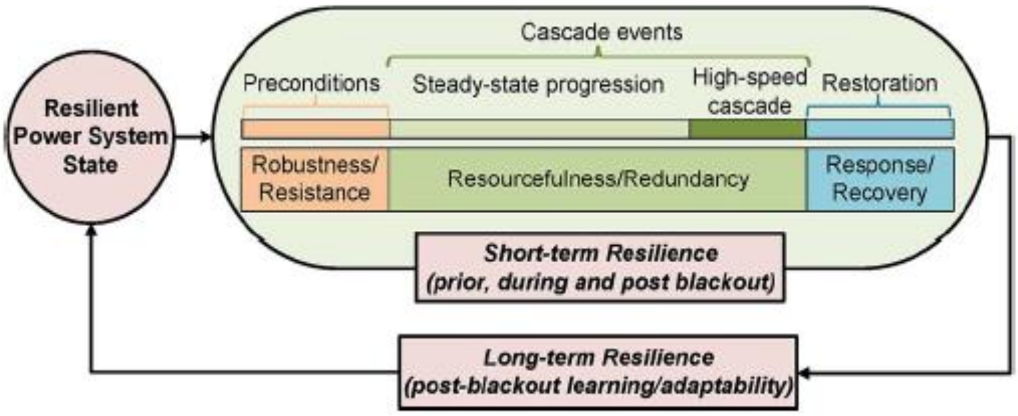


Figure 1 Short and long term resilience of power system (Panteli & Mancarella 2015)

From a climate based perspective the distribution power supply network is sensitive to impacts from both high and low temperatures, rainfalls and floods. Within the UK in 2015, for example, there were failures in the power supply network in both the cities of Rochdale[1] and Lancaster[2] due to separate flood incidents. In the United States alone, the number of weather

[1] http://www.enwl.co.uk/news-and-press/latest-news/2015/12/26/26-12-15-severe-flooding-causes-power-cuts-in-rochdale-and-lancashire-(12-20-update)

[2] http://www.enwl.co.uk/news-and-press/latest-news/2015/12/06/06-12-15-lancaster-and-surrounding-area-to-be-without-power-for-days-(06-00-update)

related power outages that occurred between 2003 and 2012 was estimated to account for costs higher than 300 billion US dollars (Gholami *et al*. 2016).

Furthermore, it is important to assess not only those areas which are directly affected by extreme events, but also those other areas which, although not being located in the damaged zone, might indirectly be affected due to various reasons. Such reasons could be the loss of generators or loads in the area directly affected by the event, causing instabilities in the grid (Figure 2). As it can be observed, if preventive actions are taken into consideration, the system resilience is recovered in a much shorter period of time.

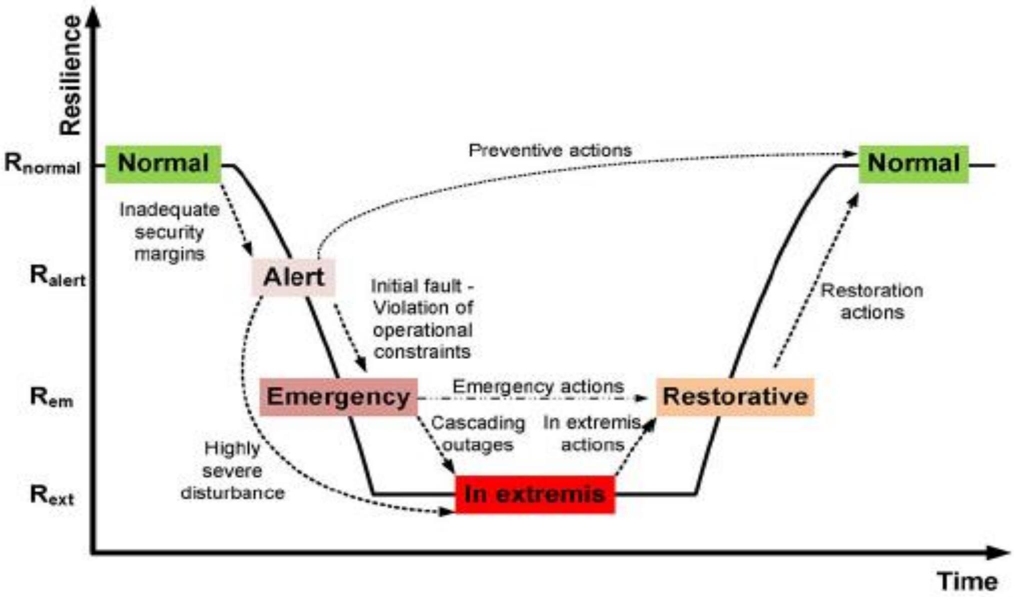


Figure 2 - Conceptual resilience curve (Panteli & Mancarella 2015)

Quantifying electric power grid resilience to cope with climate change on urban areas is an important current challenge due to recent notable disasters over developed nations, as well as the increasingly dependence of our society on electricity. However, obtaining resilience metrics in power grids is a complex task that involves taking into consideration several aspects such as the effect and influence of humans in power system's performance, the interdependences between loads and generating units, or the shift towards a more distributed customer system where local energy storage systems and smart grid technologies play a major important role, among others. As stated by Gholami *et al*. 2016 current centralised power systems i.e. energy flow going downstream, from generation plants to loads, pose a limit to the recovery of critical loads as the restoration process is also top-down. The highlighted weaknesses of centralised power systems have illustrated the opportunities/need of Distributed Energy Resources (DER), distributed energy storage (e.g. batteries, electric vehicles) and micro-grids to enhance resilience.

By observing in detail the components within the distribution power network, fragility curves (Figure 3) could be used to find out the probability of failure depending on different climate variables, for example, wind speed, temperature and water coverage. For example, there are transformer substations scattered throughout the city that are responsible for stepping down voltages for domestic and commercial uses that are susceptible to failure. The probability of failure of these electrical assets could serve as means of finding out the vulnerable zones within the electrical system. For instance, from a flooding perspective, the proposal here would be to map the locations of substations and to overlap them with flood depth maps with associated depth damage curves. In this way, it would be possible to establish the likelihood of failure of these substations throughout the city, as stated Panteli & Mancarella (2015).

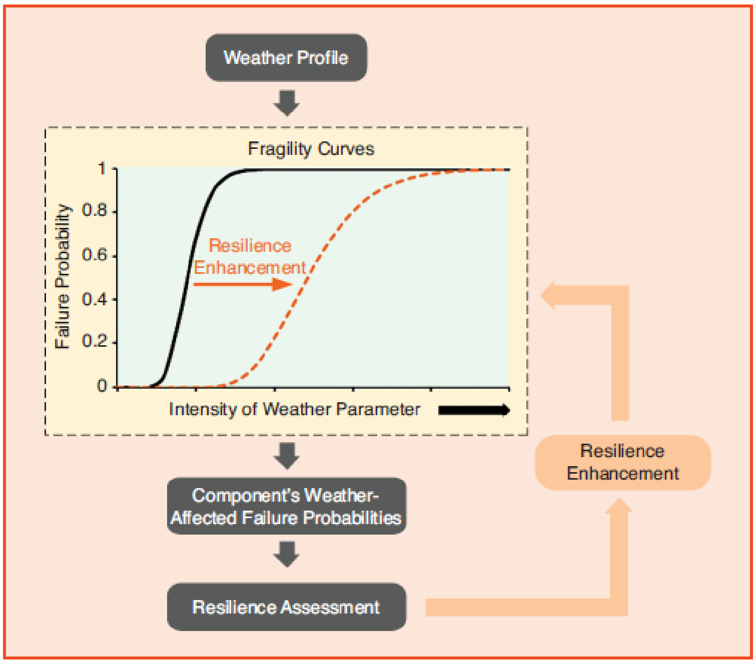


Figure 3 - Evaluating and enhancing resilience to weather events using fragility curves Panteli & Mancarella (2015)

## 3.1.1 Quantifying Impacts on Energy Supply

With the aim of quantitatively representing power grid's performance during natural disasters or other extreme events, Kwasinski (2016) proposed the following metric for resilience applied to the energy supply sector based on the definition for resilience currently adopted by several agencies and national laboratories around the world, such as for example Department of Energy (DOE) in U.S. or U.K. Cabinet office (i.e., "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions").

$$R_B = \frac{\sum_{i=1}^{N} T_{U,i}}{NT} = \frac{\sum_{i=1}^{N} T_{U,i}}{\sum_{i=1}^{N}(T_{U,i} + T_{D,i})}, \qquad (1)$$

Here (in Equation 1) $R_B$ is the base resilience, *N* is the number of loads in the studied system, *T* is the period of time under consideration, $T_{U,i}$ is the part of *T* when a load *i* is able to receive electric power and $T_{D,i}$ is the remaining portion of time *T* when load *i* may not able to receive electric power (downtime).

According to the literature (Willis & Loa 2015), there are multiple ways to assess how resilience is managed and measured in energy systems. To measure system performance, System Operators and Utilities have developed several performance metrics concerning different critical aspects such as energy delivery, reliability, power quality and sustainability, among others. Based on Kwasinski (2016), power outages are considered the main performance indicator to evaluate the impacts of extreme events on the power grid. Supply continuity is determined by the amount of interruptions and therefore, System Operators and Utilities aim at minimizing interruptions in order to maximize the power availability. Since affections to the power system are very particular for each case, it is hard to define reference values.

As it can be seen in Figure 4, the period of time ranging from one extreme event to the next one can be divided into different phases:

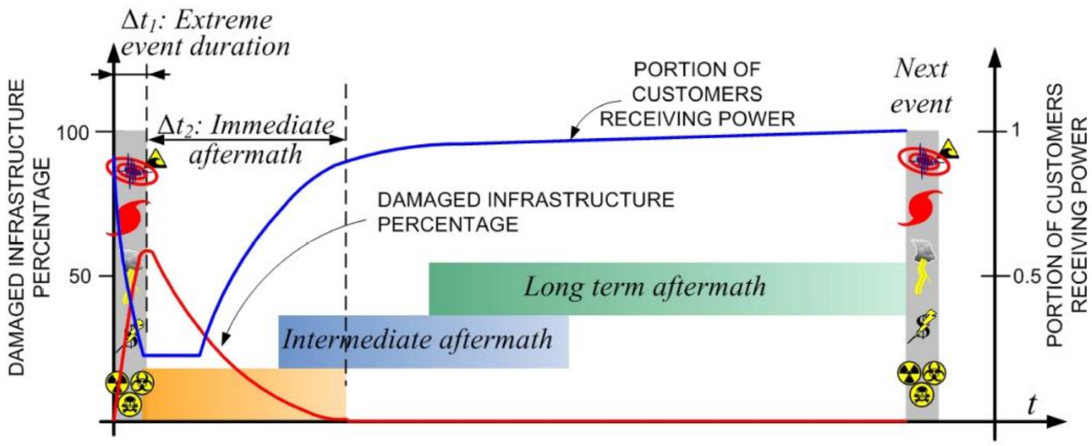


Figure 4 - Representation of the phases of an extreme event and their aftermaths (Kwasinski 2016)

Based on reliability theory and *IEEE* Standards, electric utilities consider several supply continuity indicators as resilience metrics of the power grid. Additionally, power quality is determined by both the voltage waveform, which is the quality of the product delivered, and the supply continuity, which determines the availability of the product.

Regarding the supply continuity, the *IEEE Guide for Electric Power Distribution Reliability Indices* includes sustained interruption metrics that can be classified as:

**a) Customer oriented indices**

- **System Average Interruption Frequency Index (SAIFI):** this index indicates the average number of interruptions by served customer in a defined period of time. The unit is interruptions per customer in one year.

$$SAIFI = \frac{\sum Total\ number\ of\ customers\ interrupted}{Total\ number\ of\ customers\ served} \tag{2}$$

- **System Average Interruption Duration Index (SAIDI):** this index indicates the average outage duration for each customer served. It is usually measured in minutes or hours. The unit is minutes interrupted per customer in one year.

$$SAIDI = \frac{\sum Customer\ interruption\ durations}{Total\ number\ of\ customers\ served} \qquad (3)$$

- **Customer Average Interruption Frequency Index (CAIFI):** this index indicates the average frequency of interruptions by customer interrupted. The unit is interruptions per affected customer in one year.

$$CAIFI = \frac{\sum Total\ number\ of\ customers\ interruptions}{Total\ number\ of\ customers\ interrupted} \qquad (4)$$

- **Customer Average Interruption Duration Index (CAIDI):** this index indicates the average outage duration by customer interrupted. The unit is minutes interrupted per affected customer in one year.

$$CAIDI = \frac{\sum Customers\ interruption\ duration}{Total\ number\ of\ customers\ interrupted} = \frac{SAIDI}{SAIFI} \qquad (5)$$

- **Average Service Availability Index (ASAI):** this index indicates the fraction of time that service was available to a customer during the defined reporting period. It is normally expressed as a percentage of hours in a year where 8760 = 24 x 365.

$$ASAI = \frac{Customer\ time\ service\ availability}{Customer\ time\ service\ demands} = 1 - \frac{SAIDI}{8760} \qquad (6)$$

**b) Load oriented indices**

- **Average System Interruption Frequency Index (ASIFI)**: this index indicates the equivalent number of interruptions out of the total served load.

$$ASIFI = \frac{\sum Total\ connected\ kVA\ of\ load\ interrupted}{Total\ connected\ kVA\ served} \qquad (7)$$

- **Average System Interruption Duration Index (ASIDI)**: this index indicates the equivalent duration of interruptions out of the total served load.

$$ASIDI = \frac{\sum Connected\ kVA\ duration\ of\ load\ interrupted}{Total\ connected\ kVA\ served} \qquad (8)$$

**c) Generation/Transmission system oriented indices**

**Power Indices:**

- **Loss Of Load Expectation (LOLE):** this index indicates the expected number of days per year during which the system is not able to cover the daily peak demand.
- **Loss Of Load Probability (LOLP):** this index indicates the annual probability for which the system is not able to cover the daily peak demand.

**Energy Indices:**

- **Loss Of Energy Expectation (LOEE)**: this index indicates the expected energy for which the system will fail to serve during a period of time, usually considered one year.
- **Energy Not Supplied (ENS)**: this index indicates the energy that the system has not supplied during a considered period of time.

With regards to the voltage waveform, it mainly depends on the frequency and amplitude of the wave. According to Rouse & Kelly (2011) and Willis & Loa (2015), there are several disturbances which can affect the voltage waveform. Possible disturbances, which may be evaluated by means of both IEC and IEEE Standards (e.g., IEEE Std 519-2014), are described continuously.

a) Voltage dips:
The decrease, for short periods of times, of voltage regarding nominal value. The causes are mainly abrupt increases in load, such as short circuit events (Figure 5). A voltage dip or sag is the most typical type of disturbance.

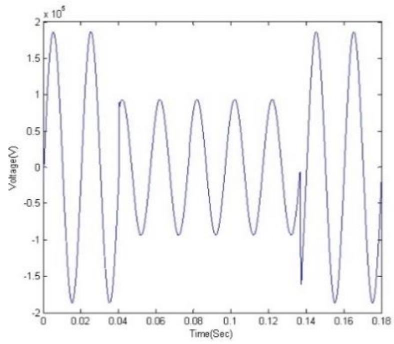

Figure 5 - Characterization of a voltage dip (PQ Problems 2017)

b) Voltage swells:
The increase, for short period of times, of voltage regarding its nominal value (Figure 6). Most of the times, the cause is an abrupt decrease in load.

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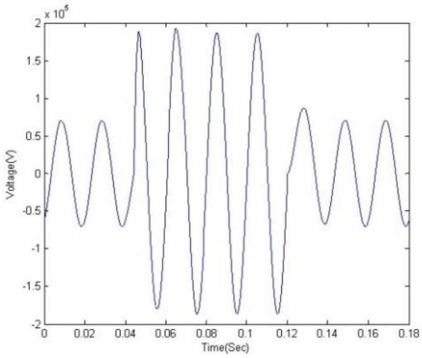


Figure 6 - Characterization of a voltage swell (PQ Problems 2017)

c) Flicker:
The intermittent increases and decrease of voltage. These fluctuations are mainly due to rapid reactive current variations in loads. The effect of flickering is visible in lamps (Figure 7).

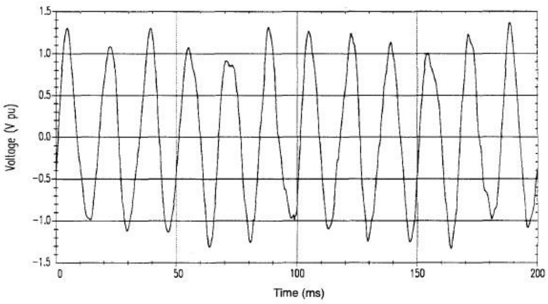


Figure 7 - Characterization of a flicker (Power Quality Basics 2017).

d) Harmonic distortion:
When some voltage components operate at off-nominal frequencies, which are multiple of the fundamental frequency. In the case of Europe, the grid operates at the fundamental frequency of 50Hz. The major cause is the high switching speed (Figure 8).

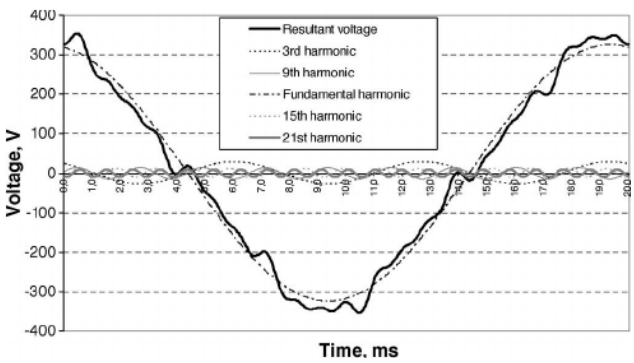


Figure 8 - Characterization of harmonics (Demoulias & Gouramanis 2017)

e) Phase unbalance

The electrical grid is a 3-phase system and when a 3-phase load is connected to this grid but without an equal distribution, a phase unbalance takes place (Figure 9).

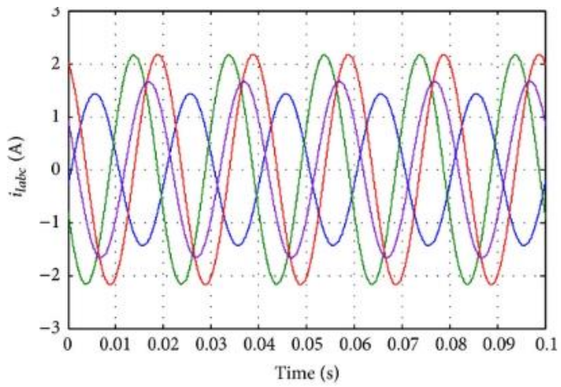



Figure 9 – Characterization of a three-phase unbalanced load current (Chelli et al. 2015)

As general concepts for maintaining the stability of the grid after a disturbance, some parameters such as the voltage and the power factor are essential when analysing the results of a simulation. The supply of reactive power is necessary to maintain the desired voltage level since the more reactive power injected, the higher the voltage will be. On the other hand, the power factor, which is the ratio between the real power and the apparent power, must be controlled in order to make sure it stays within the admissible limits.

### 3.1.2 Summary of impact quantification methods on energy sector to be employed within RESCCUE

Within the energy sector, two specific areas/means of impact quantification have been identified that are: Fragility Curves & Performance Indices. Both of these methods can be interlinked within the quantification/estimation of impacts whereby fragility curves can be employed to obtain spatial information in relation to risks of infrastructure failure and the performance indices serves as a means of quantifying the impacts in meaningful terms for the energy sector. Table 2 provides a summary of how these methods outlined are to be utilised in RESCCUE.

Table 2 - Application of impact quantification of energy supply disruption within RESCCUE

| Identified Impact Quantification Summary | Applied RESCCUE methodology |
|---|---|
| Fragility curves | Identify key infrastructure within the network that is susceptible to disruption.<br><br>Information about infrastructure characteristics, their spatial distribution and infrastructures dependent upon their services will be compared to data outputs from climate and hydraulic models such as climate data and flood depth maps to quantify risks.<br><br>Look at means of creating fragility style curves for CIs. |
| Performance Indices (SAIFI, SAIDI, CAIFI, and CAIDI) | For the quantification of impacts of energy disruption the energy sector utilises indices as performance indicators. Linking information from spatial analysis of impacts from climate and hydraulic variables the work in RESCCUE intends to utilise SAIFI, SAIDI, CAIFI, CAIDI indices. Similar based indices in relation to disruption are to be applied in the analysis of telecommunications.<br><br>With energy supply information being sensitive information, RESCCUE is proposing (where donor to receiver supply data is lacking) a fuzzy based analysis (as highlighted later in section 4) for determining potential impacts.<br><br>In instances where there is greater data availability (perhaps for key sectors within a city and with adequate non-disclosure agreements in place) information about donor and receiver along with redundancy information can be incorporated into the HAZUR® tool for further analysis of cascading implications to receiver infrastructures and services resulting from service disruption. |

## 3.2 **Flood based impacts on infrastructures**

### 3.2.1 Direct damage methodology and tool

Work within the EU CORFU project investigated the financial impacts as a result of flood damage at a micro-scale level. In this work flood maps were combined with vulnerability maps derived via depth-damage curves that are linked to land use (Velasco et al. 2016).

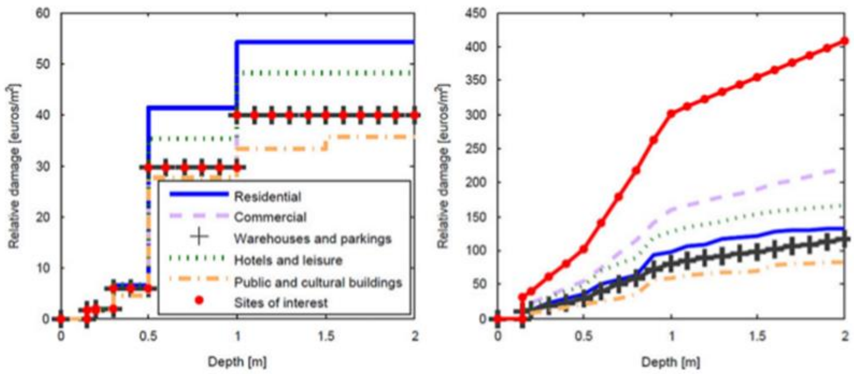



Figure 10 - Depth damage curves for buildings (left) and contents (right) whilst factoring in local conditions of the Raval district from Velasco *et al*. (2016)

Further work by Chen *et al*. (2016) led to the creation of a damage assessment tool. The damage assessment tool quantifies the damage for each spatial location by overlapping the hazard characteristics and object attributes such as land-use to a lookup table that contains the damage function for that particular land-use type. The tool was designed to deal with different data format combinations (raster and vector) of hydraulic and land-use data. With the output data from the hydraulic models used being in a raster grid format, the damage assessment tool was designed to rasterise the infrastructure data (commonly found in vector format) and apply land use values for reference to each cell accordingly. This allows for a raster to raster style analysis. One of the factors to consider when rasterising vector data however is the impact in change of spatial resolution. With this, Chen *et al*. (2016) looked at these effects along with considering additional variables such as level of impacts relating to flood duration and possible future urban growth scenarios. Within the RESCCUE project these influences will be investigated along with the standard damage assessment curves as a means of quantifying uncertainties of damage and predicting future damage costs due to climate change scenarios.

### 3.2.1.1 Direct damage to buildings

For the assessment of the direct damages three different types of data are required: *land use information*, *flood maps* and *flood depth damage curves*. Land use information captures the type, morphology and use of the buildings in the study case area. Flood maps gather the information about hydraulic variables, namely water depths and flow velocities. And flood depth damage curves are functions that relate the type of building and its characteristics with the depth of floods used to quantify the damages resulting from each flood event.

Firstly land use information for each case study will be sourced as the underlying dataset for damage assessment; in the case of the Barcelona case study, for example, the "Spanish Statistical Office" or Spanish "National Cadastre" will be consulted. Data at building level can be found here and are both publically and freely available via their website. For the type of floods (ranges in depths) that affect Barcelona, the only data necessary are related to ground floor and the basement level of buildings. Thus, the maps will be produced with the information regarding the type of use, the dimension of the buildings and the situation within the case study area. Figure 11 shows a comparison of land uses at each of the levels within the city of Marbella investigated within the PEARL project.

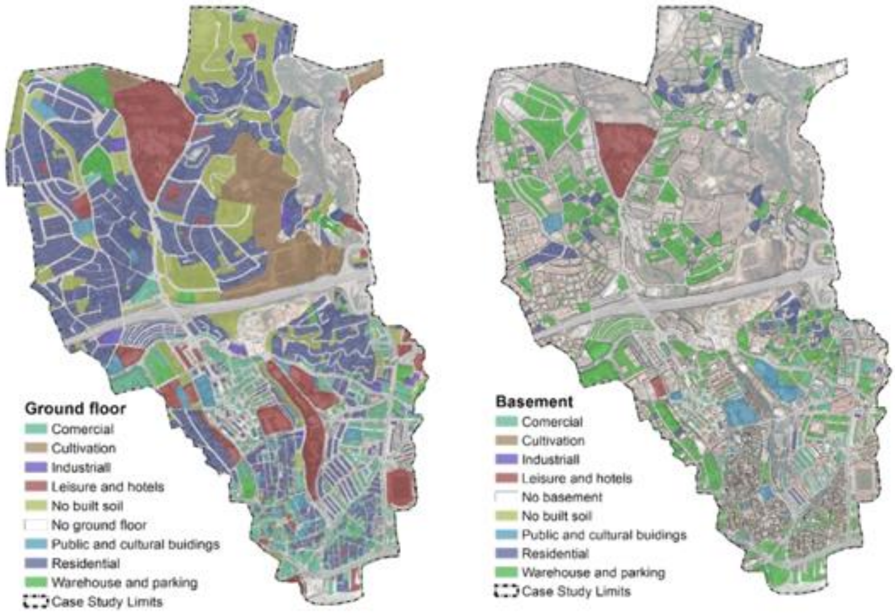



Figure 11 - Example of Land use maps for Marbella Case Study, ground floor (left) and basement (right)

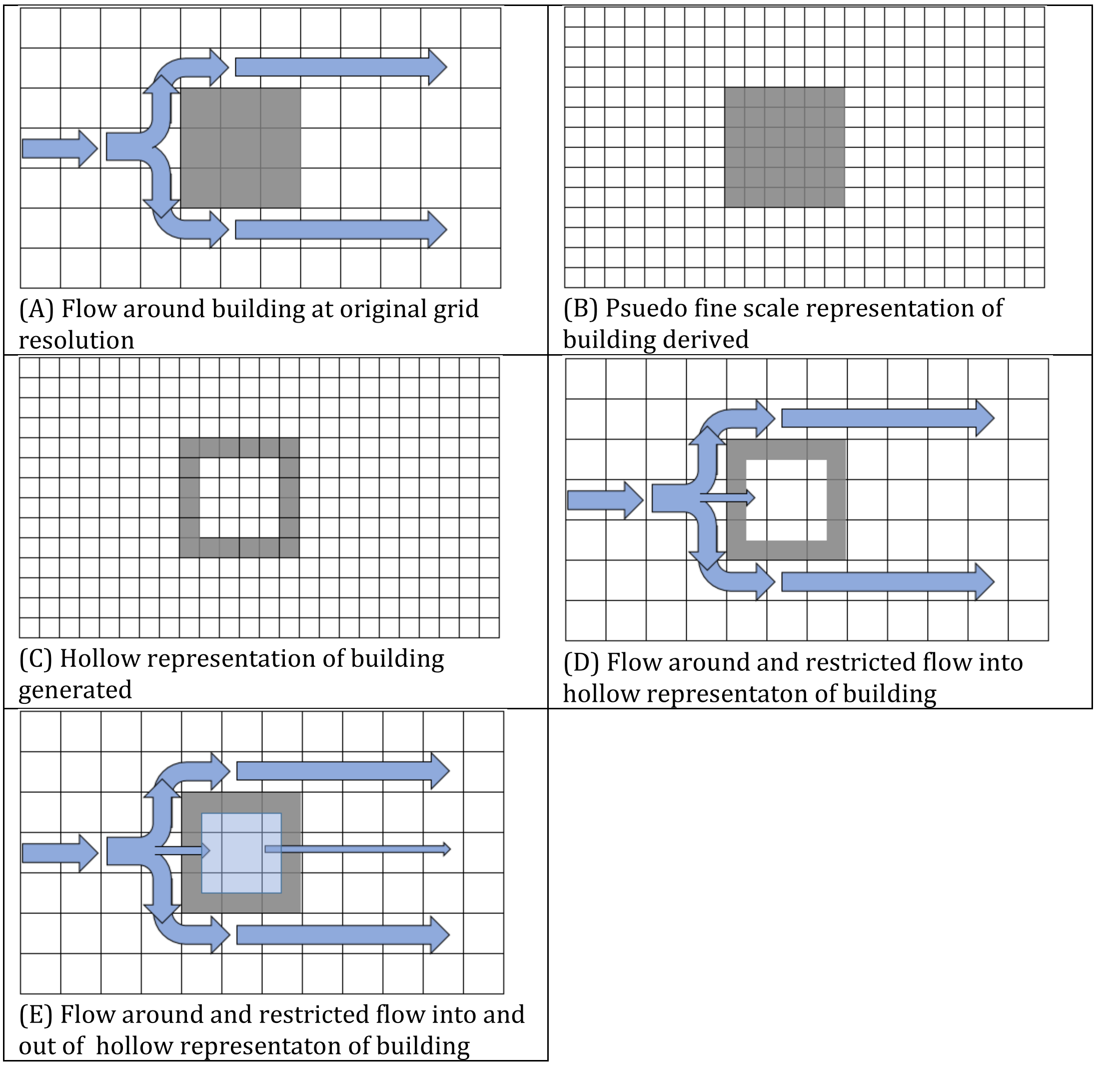
Secondly, flood maps will be created using the 1D-2D coupled model in order to assess the water depth per each building. Flood maps will be produced per different return period's rainfalls.

### 3.2.1.2 Permeability and water ingress into buildings

The flood depth damage curves outlined earlier depicted the relationship between water depths and damage to contents within buildings. Within conventional urban flood models, buildings are either removed or treated as solid obstacles. For the former, the blockage effect of buildings on flow propagation is not represented, while for the latter, the flow moving around and between buildings and the accuracy of the movement of flow is dependent upon the digital surface model (DSM) grid resolution. Either case will not accurately simulate the flood depths inside buildings. Previous work by Evans (2010) and Chen *et al*. (2012) investigated the use of a multi-layered approach to simulated high spatial resolution building features within 2-Dimensional coarse-grid resolution flood models. This approach was primarily designed to allow for the accurate routing of surface water flow and subsequent flood depth predictions whilst keeping the computational run-times short but also enabled to allow flow through narrow (where their dimension is less than raster cell grid size e.g. < 1 m) alleyways between buildings.

It is being considered that this approach could be utilised as a means of allowing restricted flow into and through building structures to achieve more accurate representations of flood depths within buildings to improve quantification estimates of impacts to building contents.

Figure 11 partly shows the methodology for altering the representation of a building feature to allow for surface flow to enter both into and out of the building. This is achieved by creating a hollowed out pseudo fine scale representation of building features within the DSM then using the multilayer approach to represent this hollowed out building feature back into its original resolution. Within a grid cells (usually street facing and away-street facing) a high (*N* → 1) Conveyance Reduction Factor (*CRF)* value is given that represents doorways. A *CRF* value that tends to but less and not equal to 1 allows for representation of heavily restricted flow through gaps between the door and the door frame. This CRF representation approach can be taken one step further whereby the *CRF* value at door locations can be dynamically changed so that once depths surrounding the outside the building reach a specified threshold the *CRF* value could be reduced to simulate door failure and allow for sudden increase of flow into the building feature. Whereas previous approaches estimated depths within buildings based on depths surrounding the feature this approach allows for potentially more realistic simulation of flood depths within buildings and their impacts on building contents.



(A) Flow around building at original grid resolution

(B) Psuedo fine scale representation of building derived

(C) Hollow representation of building generated

(D) Flow around and restricted flow into hollow representaton of building

(E) Flow around and restricted flow into and out of hollow representaton of building

Figure 12 - Representing porosity of building features using a multi-layer *BCR* & *CRF* approach

A secondary approach for estimating ingress into buildings is where buildings are initially treated as solid objects and post analysis is carried out on the resulting flood depth map outputs. Here flood maps will be obtained on the basis of an unstructured mesh that covers all the streets of the analysed catchment. A toolbox developed by UNESCO-IHE in the framework of PEARL project and another application developed by AQUATEC in the framework of CORFU project could be utilized in order to calculate, automatically, the mean water depth around any building of the case study, based on the flood maps previously obtained. Once an average water depth is associated to each building, a new methodology, based on conversations with experts in damages due to floods, is proposed to determine the water depth inside the building. The main idea in this approach is that a “Sealing Coefficient” ($C_s$) will determine the difference between the water depth outside and inside the difference ($Y_{GF}/Y_o$). It is assume that the residence time of the flooding is not enough for the building to leak until the water levels outside and inside become equal. Cases in which water enters directly through open doors and windows are not considered because these are regarded as being closed with the assumption the public have been properly warned of potential flooding. Therefore, the Sealing Coefficient will be one of the most important parameters of calibration for the damage model. It takes a value lower than the unit and was adjusted based on damages due to real flood events. Its value was established as 0.2 which indicates that the water level inside the building is a 20% of the water level outside. On the other hand, according to conversations with experts, a different water depth should be considered in the ground floor ($Y_{GF}$) and in the basement ($Y_B$). In some cases, the water depth beside the building wall ($y_o$) can be recalculated by subtracting 15 cm from the previously calculated average water depth around the buildings. This is assumed as a generalised presence of sidewalks across the studied urban area and the adopted value of reduction (15 cm) is considered as an average height of the kerb.

Whereas the water depth in the ground floor will be lower than the outside one, basements act as small water storage tanks and water depths can become higher than those present on the streets. According to experts’ advice, water depths in basements ($Y_B$) can be considered as double of the water depth beside the building wall ($y_o$). However, three kinds of building can be found within the studied area, whether those are formed by ground floor and basement (Type I), only ground floor (Type II) or only basement (Type III). When dealing with Type I previously proposed rules are still established but a maximum depth of 20 cm is allowed in the ground floor. According to experts, when water leaks to a ground floor and there is a basement downstairs, water level rises until a certain level (20 cm approximately) and then it remains fixed while basement water depth still rises. A scheme of the different types of buildings and water depths is presented in Figure 13.

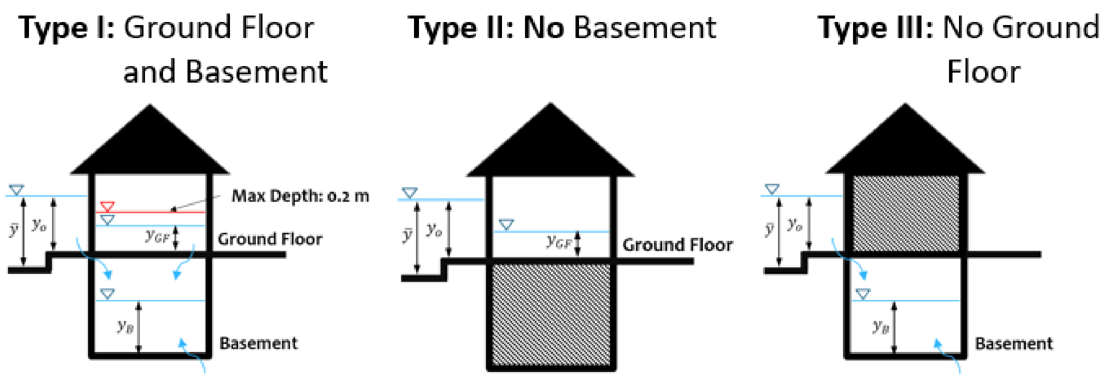



Figure 13 - Different types of buildings and water depths considered in the buildings damage model

Therefore, this model will be implemented in the GIS software in order to establish a water depth inside the buildings, based on the previously presented rules.

In order to assess the direct economic damage it is necessary to have the depth damage curve per each type of land use. As said, flood Depth Damage Curves (DDC) are functions that relate the water depth in each kind of land use with the flood damage per square meter. Moreover, the depth damage curves are developed for contents and for buildings. A detailed study of the past flood consequences using data from Consorcio de Compensación de Seguros (CCS, Spanish national reinsurance company) is currently being conducted in order to develop DDC for Barcelona research site. Per each type of building a typical example is defined. Then, the expected damages for the typical example are assessed both for the building and for the content to create two different DDC. Finally, the DDC will be normalized per square meter in order to be applied in every building of each type. The tailored damage curves developed for Marbella case study in the framework of the project PEARL are shown in Figure 14 as example.

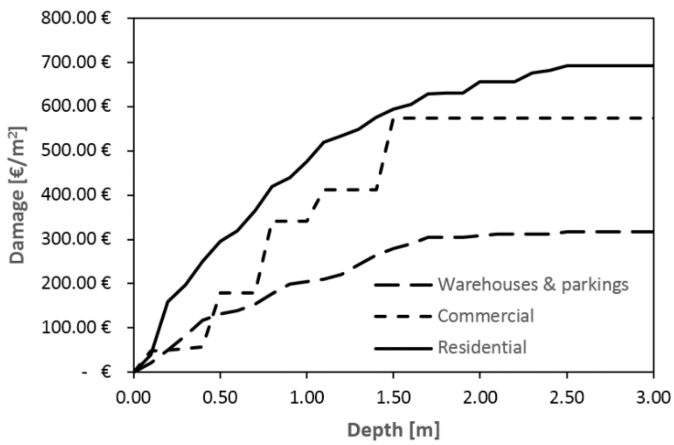



Figure 14 - Damage curves for Marbella case study (PEARL project)

Once water depths are assigned to each building, separately between ground floor and basement, within the study area, another toolbox developed by the University of Exeter for the project CORFU will be employed in order to calculate the damages.

Damage maps will be elaborated according to the different return period considered and represented per building level: ground floor and basement. A calibration process will be conducted based on damages caused by a real floods. Regarding the “Sealing Coefficient” (Cs), it will be adjusted up to a value of 0.2.

Finally, the expected annual damage (EAD) will be calculated (Velasco *et al*. 2016). EAD is the aggregation of the expected damage per each return period, taking into account the occurrence probability of each event. It is calculated as the area below the curve in Figure 15. The result of the EAD is used as an indicator of the magnitude of flooding events. It is useful to compare current state with a post-measures state in order to take more informed decisions in urban planning. The goal is to maximize the reduction of the EAD after applying a set of adaptation measures.

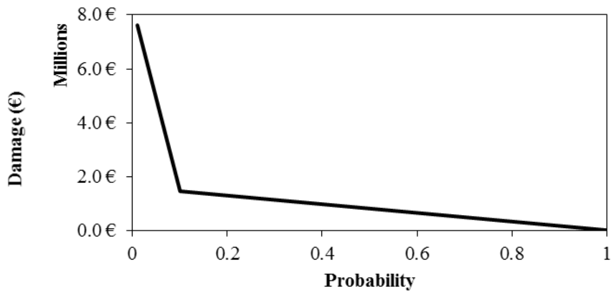



Figure 15 - Example of the EAD for Marbella case study (PEARL project)

### 3.2.1.3 Flood duration

The duration of which flood water is in contact with critical infrastructures (CI) can affect the amount of damage transferred to the CI or the contents within. Although monitoring flood duration (depths above specific thresholds) could be carried out within hydraulic simulations it could add significant demand to the computational processing. An alternative to this that was used by Chen et al. (2016) was to take snapshots at specific time intervals and then analyse this information once the entire simulation is complete. The damage impact assessment tool can analyse the flood characteristics (depth and/or velocity) and calculate level of damage via duration dependent hazard-vulnerability functions.

### 3.2.1.4 Spatial resolution

When generating land use rasters based on vector inputs, the percentage occupancy of the vector data within the overlaying grid cell will determine the land use classification of that cell. Therefore the chosen grid resolution for the rasterization process can have significant impact on the percentage distribution of land use types. Figure 16 shows how the variances in cell size can lead to over and under estimation of land use classes.

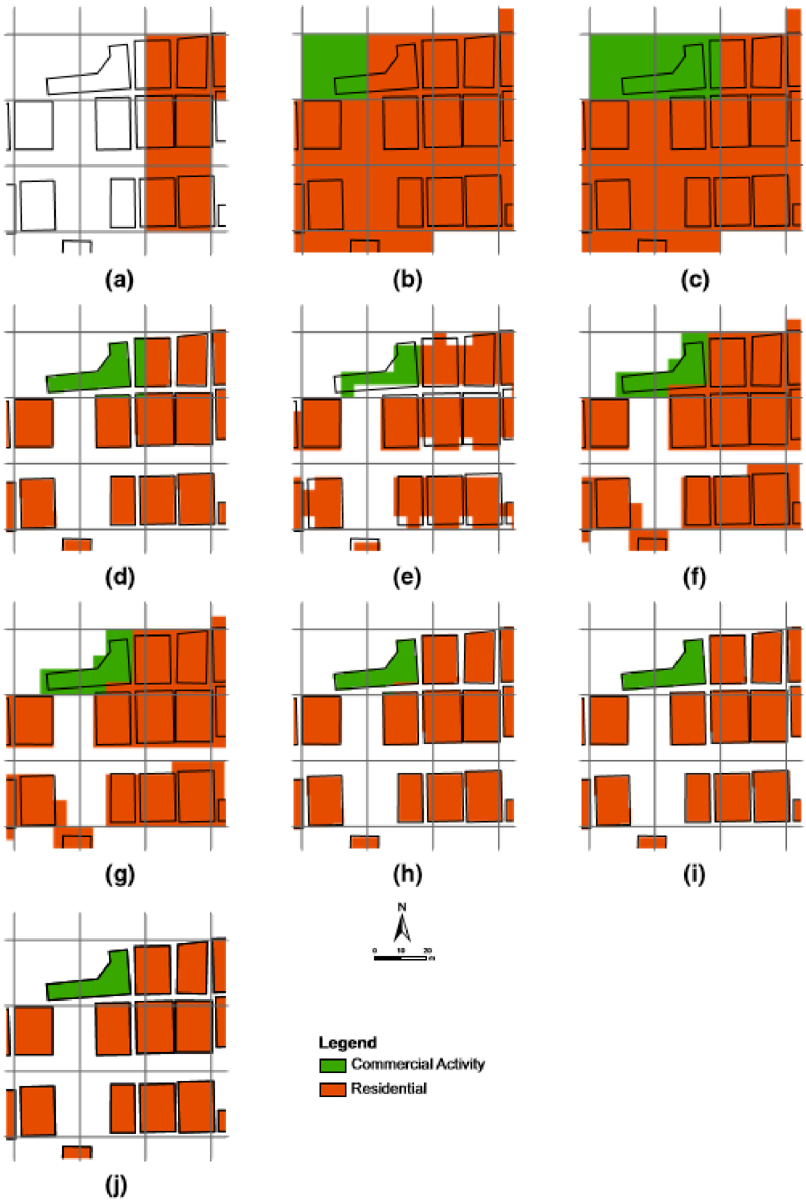



Figure 16 - The representations of building attributes using different raster resolutions, aggregating methods and masking. (a) 25 m raster converted from building polygons using ArcGIS built-in ''Polygon to Raster'' function. (b) 25 m raster aggregated from 1 m raster that is converted from building polygons using ArcGIS built-in ''Aggregate'' function. (c) 25 m raster aggregated from 1 m raster that is converted from building polygons using the ''Aggregate'' function developed in Fortran code. (d) Masked 1 m raster using the aggregated 25 m raster in (c). (e) 5 m raster converted from building polygons using ArcGIS built-in ''Polygon to Raster'' function. (f) 5 m raster aggregated from 1 m raster that is converted from building polygons using ArcGIS built-in ''Aggregate'' function. (g) 5 m raster aggregated from 1 m raster that is converted from building polygons using the ''Aggregate'' function developed in Fortran code. (h) Masked 1 m raster using the aggregated 25 m raster in (g). (i) 1 m raster converted from building polygons using ArcGIS built-in ''Polygon to Raster'' function. (j) Original building polygons (Chen et al. 2016)

The choice of analysing cell size and masking cell size can have significant effects when estimating damages from flood events as shown in Table 3. The obvious solution would be to go with the highest resolution possible to yield the most accurate results though in doing so there is a trade off in computational time (Table 4).

Table 3 - Total flood damage for 100-year event in Dhaka city with different analysing and masking cell sizes (Chen et al. 2016)

| Case | Analysing cell size (m) | Masking cell size (m) | No/ buildings with flood damage | Total flood damage ($10^6$ BDT) |
|---|---|---|---|---|
| **1** | 1 | 1 | 67,046 | 1642.8 |
| **2** | 5 | 1 | 67,278 | 1642.7 |
| **3** | 25 | 1 | 67,330 | 1642.2 |
| **4** | 5 | 5 | 55,734 | 1540.2 |
| **5** | 25 | 5 | 55,920 | 1539.6 |

Table 4 - Computational time of subtasks for 5 test cases outlined in Table 2 (Chen et al. 2016)

| Subtask | Time spent (s) | | | | |
|---|---|---|---|---|---|
| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
| **Polygon to raster** | 192.77 | 194.80 | 195.15 | 164.35 | 164.92 |
| **Shapefile copying** | 55.70 | 55.57 | 55.58 | 55.58 | 56.33 |
| **Raster to float** | 25.87 | 26.62 | 26.87 | 0.95 | 1.02 |
| **Aggregating** | 8.35 | 1.87 | 1.98 | 0.22 | 0.22 |
| **Damage calculating** | 17.83 | 0.50 | 0.13 | 0.10 | 0.07 |
| **Results associating** | 65.35 | 66.58 | 66.47 | 66.50 | 66.98 |
| **Summing up** | 6.85 | 2.20 | 2.30 | 1.07 | 1.10 |
| **Other time** | 0.77 | 1.18 | 0.87 | 0.63 | 0.87 |
| **Total** | 373.47 | 349.28 | 349.30 | 289.42 | 291.58 |

With the masking cell size is sensitive to accurate estimation, it is recommended to use finest masking resolution for evaluating the flood damage.

### 3.2.1.5 Urban growth

The Urban Growth Model (UGM) used within the CORFU project was developed by Veerbeek *et al*. (2015) to predict future changes in land cover based on historic land use/land cover data and various terrain characteristics. The UGM only provides land cover classifications that represent the density of built-up areas and does not directly correspond to specific land use. It is not, therefore, placing new buildings into the model, it is merely specifying the percentage change in land use types based on its' growth predictions. Figure 17 shows the LULC 2010 baseline for a region in Dhaka and the estimated damages that result from flooding. Figure 18 shows how the LULC data has changed following a Business As Usual (BAU) growth for 2050 and the changes in estimated damage values from flooding as a result of these land use changes.

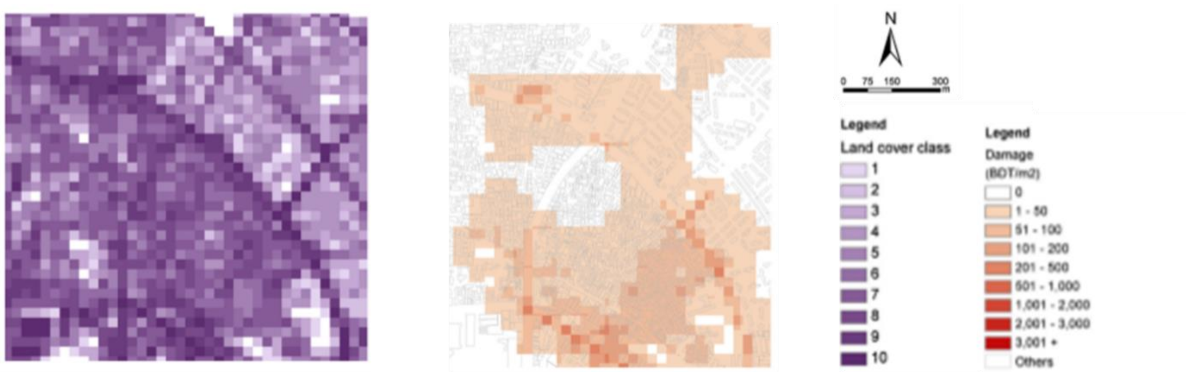


Figure 17 - LULC for 2010 baseline and estimate flood damage per unit area using LULC (Veerbeek *et al*. 2015)

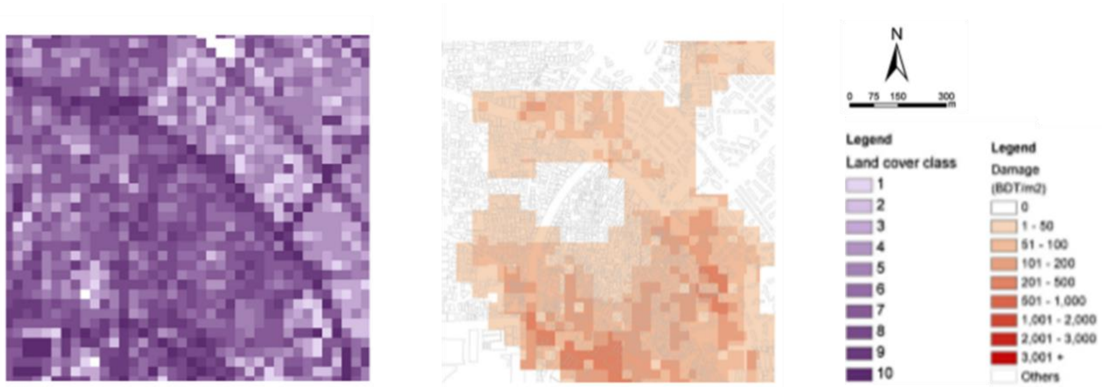


Figure 18 - LULC for BAU high-growth 2050s based on projected UGM and flood damage per unit area based on this derived LULC data (Veerbeek *et al*. 2015)

Each land cover class relates to a different percentage distribution of building types/uses within that cell. Table 5 shows the percentage distribution of land cover classes that are depicted in Figures Figure 17 & Figure 18. Figure 18 shows that based on urban growth prediction for Business As Usual (BAU) scenario there are increased losses as a result of densification and spread of built-up areas.

Table 5 - The building components for different land use classes (Chen et al. 2016)

| **Land cover class** | **Building use** | | | | | | **Total built-up area (%)** |
|---|---|---|---|---|---|---|---|
| | **Commercial activity (%)** | **Education & research (%)** | **Governmental services (%)** | **Manuf. And processing (%)** | **Mixed use (%)** | **Residential (%)** | |
| **1** | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | 2.8 | 3.10 |
| **2** | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 7.8 | 8.80 |
| **3** | 1.2 | 0.5 | 0.2 | 0.2 | 0.4 | 14.3 | 16.80 |
| **4** | 2.0 | 0.9 | 0.2 | 0.5 | 0.7 | 19.7 | 24.00 |
| **5** | 3.0 | 1.0 | 0.3 | 0.6 | 1.4 | 26.8 | 33.10 |
| **6** | 4.1 | 1.0 | 0.4 | 0.8 | 2.8 | 32.8 | 41.90 |
| **7** | 5.1 | 0.9 | 0.3 | 1.1 | 4.9 | 35.4 | 47.70 |
| **8** | 8.5 | 1.0 | 0.3 | 2.0 | 8.7 | 31.8 | 52.30 |
| **9** | 14.8 | 1.0 | 0.8 | 5.3 | 10.1 | 19.5 | 51.50 |
| **10** | 24.0 | 2.1 | 1.7 | 13.3 | 3.5 | 11.8 | 56.40 |

### 3.2.2 Update of depth-damage curves in three research sites

The traditional methodology to develop depth damages curves entails a definition of the typical building for each case study and the definition of the expected damages and expected costs of reparation or substitutions for contents and buildings. Hence, the replicability of this methodology is complex and time-consuming.

To improve the replicability of the methodology to other case studies, an alternative methodology for the development of the depth damage curves is proposed. This new methodology consists in selecting the most similar depth damage curves available, and adapt them to a new case study by applying some economic indicators. This methodology was implemented in the Marbella case study in PEARL project, updating the depth damage curves developed for Barcelona in CORFU project (Velasco *et al.* 2016). A comparison between the results of the traditional methodology and the new one will be done during the final stage of PEARL project.

A description of the economic indicators selected for adapting the new depth damage curves is shown in Table 6.

Table 6 - Description of economic indicators selected for adapting new depth damage curves

| Economic Indicator | Description |
|---|---|
| GDP (Gross Domestic Product) per capita | GDP per capita is a wealth indicator of widespread and standardised use. Easy to access and with data available at municipality level, which is a fundamental issue for developing curves at city level. Is it useful for adapting curves both for content and buildings, since personal wealth is directly linked with assets' value. |
| GDP (Gross Domestic Product) per declarant | Likewise, GDP per declarant is also a wealth indicator. The main difference with the previous one is that this indicator only contemplates the population capable of working, instead of the total population.<br>Some relevant aspects like population structure, family size, or number of people per household can be reflected with this indicator. |
| Construction prices | This indicator is useful as flood damages have a buildings repair cost associated, and that cost is represented by labour costs and building materials costs. This indicator has usually a high level of disaggregation and easy access. |
| Land registry data | Land registry is an indicator of property value. It is a good indicator as it usually has a high level of disaggregation and open access to data. |

Within the RESCCUE project, this new methodology for the development of the depth damage curves could be used by choosing the most suitable depth damage curves available (e.g. Marbella or Badalona in Spain) and adapting them to other sites like the three RESSCUE research sites (Bristol, Barcelona and Lisbon) using the economic indicators abovementioned with the objective of adapting the suitable curves to the reality of the cities in the three case studies.

The derived depth damage curves from CORFU utilised within the PEARL project have recently been updated from their 2010 values to 2015. Figure 19 shows the relative damage costs in euros per square meter for differing building classifications in Barcelona with respect to water depths derived within CORFU project in for valuations in 2010 and later adopted and revised within PEARL for 2015 costings. Figure 20 shows the relationship of water depths to damage of contents within differing building classes again for the 2010 and later revised 2015 datasets. Numerical analysis of the differences between the 2010 and 2015 datasets show a percentage rise for all classes of building damage at 6.45% with a 6.9% rise for the building contents within them.

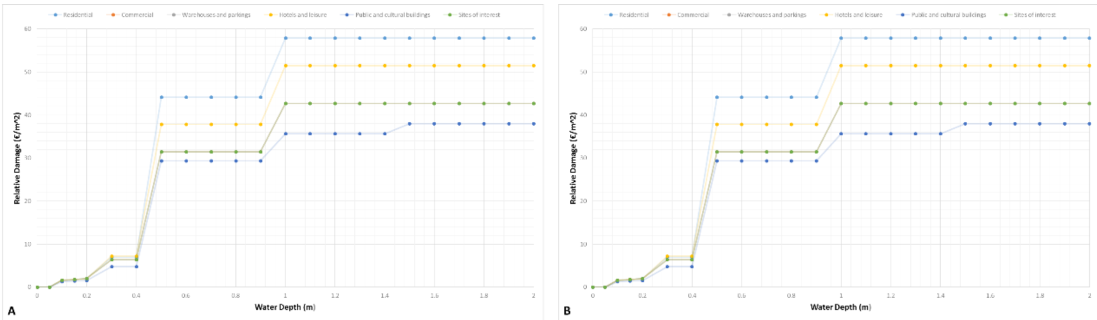



Figure 19 - Relative depth damage curves for building classes in Barcelona in 2010 (A) and 2015 (B)

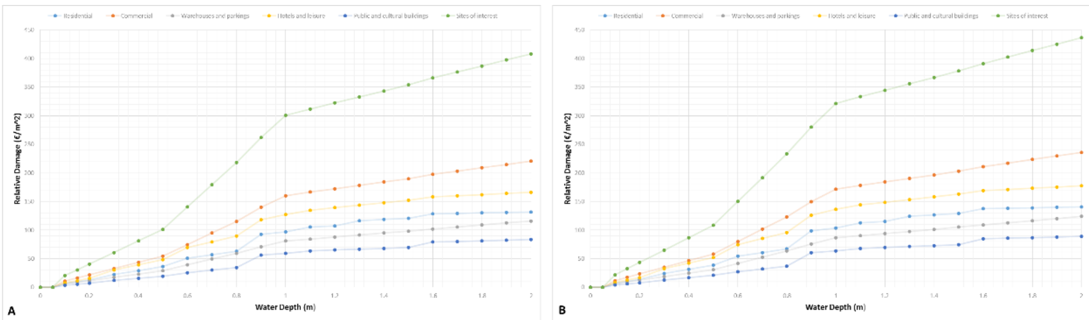



Figure 20 - Relative depth damage curves for contents of building classes in Barcelona in 2010 (A) and 2015 (B)

More recent work by Cetaqua has looked damage costs in relation to land use classifications based upon insurance claims dating back from 1999 until 2011 (Figure 21). The properties within this data are divided into 4 classes: warehouses, industrial, offices, and residential properties

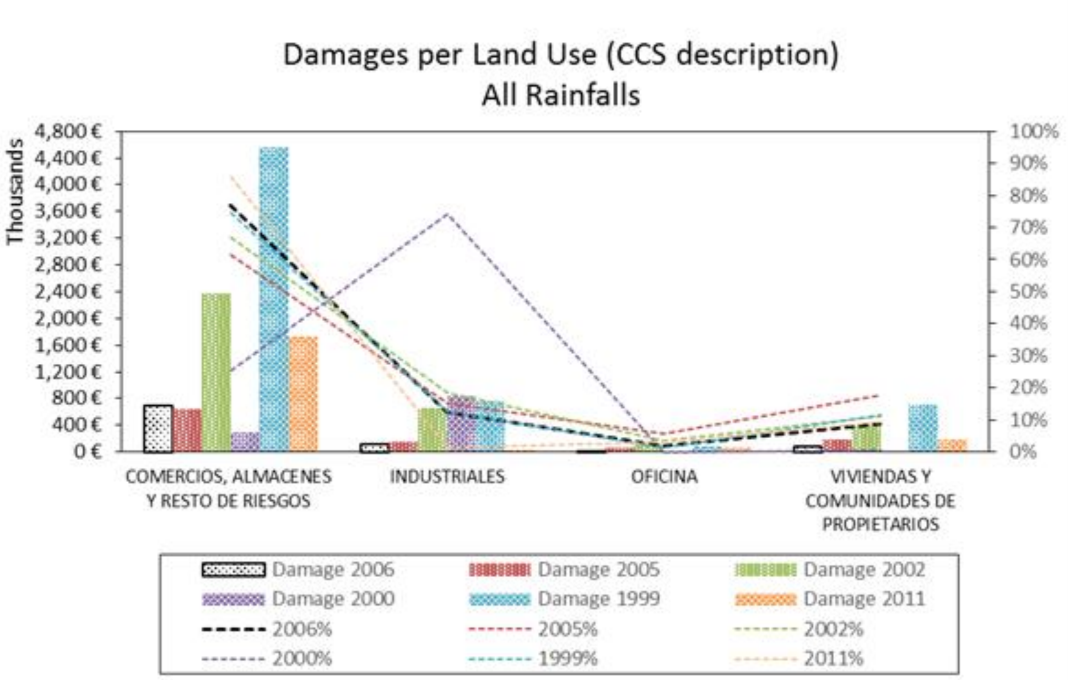



Figure 21 - Damage costs to properties as a result of pluvial flood events in Barcelona

The depth-damage relationships defined in this study however are limited to only a few land-use classifications and need to be expanded upon further for larger cities.

### 3.2.2.1 Multi-colour Manual

One means of improving the impact analysis within the case study areas is to reference building/infrastructure types with respect to the Multi-Coloured Handbook (MCH). The MCH has been designed as a guide of assessing benefits of risk management in areas of flooding and coastal erosion (Penning-Rowsell et al. 2010). The handbook itself is accompanied by a vast amount of data relating to depth-damage relationships for a large variety of land-uses within the UK. It is therefore envisioned that this data can be referenced and utilised as a means of calibrating depth damage curves in each of the study areas.

The National Receptor Dataset (NRD) ([https://data.gov.uk/dataset/national-receptor-dataset-afa171](https://data.gov.uk/dataset/national-receptor-dataset-afa171)) contains detailed information about infrastructures throughout the UK.

The NRD for the city of Bristol consists of 255,017 infrastructures that are divided up into just 15 unique MCM codes. The majority of the infrastructures within the city of Bristol are classed as “residential” and comprise of 78% of the building stock. The distribution if the infrastructure classes is outlined in Table 7.

Table 7 - MCM code count in Bristol dataset

| MCM Code | MCM Description | Feature Class Count | % of total features |
|---|---|---|---|
| 1 | All residential properties | 199,243 | 78.1 |
| 2 | Retail | 7,097 | 2.8 |
| 3 | Offices | 3,865 | 1.5 |
| 4 | Warehouse | 1,831 | 0.7 |
| 6 | Public buildings | 1,735 | 0.7 |
| 8 | Industry | 2,491 | 1.0 |
| 9 | Miscellaneous | 18,319 | 7.2 |
| 51 | Leisure | 533 | 0.21 |
| 521 | Playing fields/grounds | 12 | 0.005 |
| 523 | Sports, leisure centre | 247 | 0.1 |
| 525 | Sports stadium | 5 | 0.002 |
| 526 | Mooring/Wharf/Marina | 3 | 0.001 |
| 910 | Car park | 405 | 0.2 |
| 960 | Electricity Substation | 1,666 | 0.7 |
| 999 | Unknown | 17,565 | 6.9 |
| | | | |

Within the NDR there are numerous descriptions associated for each MCM code. Figure 22 shows the number of unique descriptions for each MCM code.

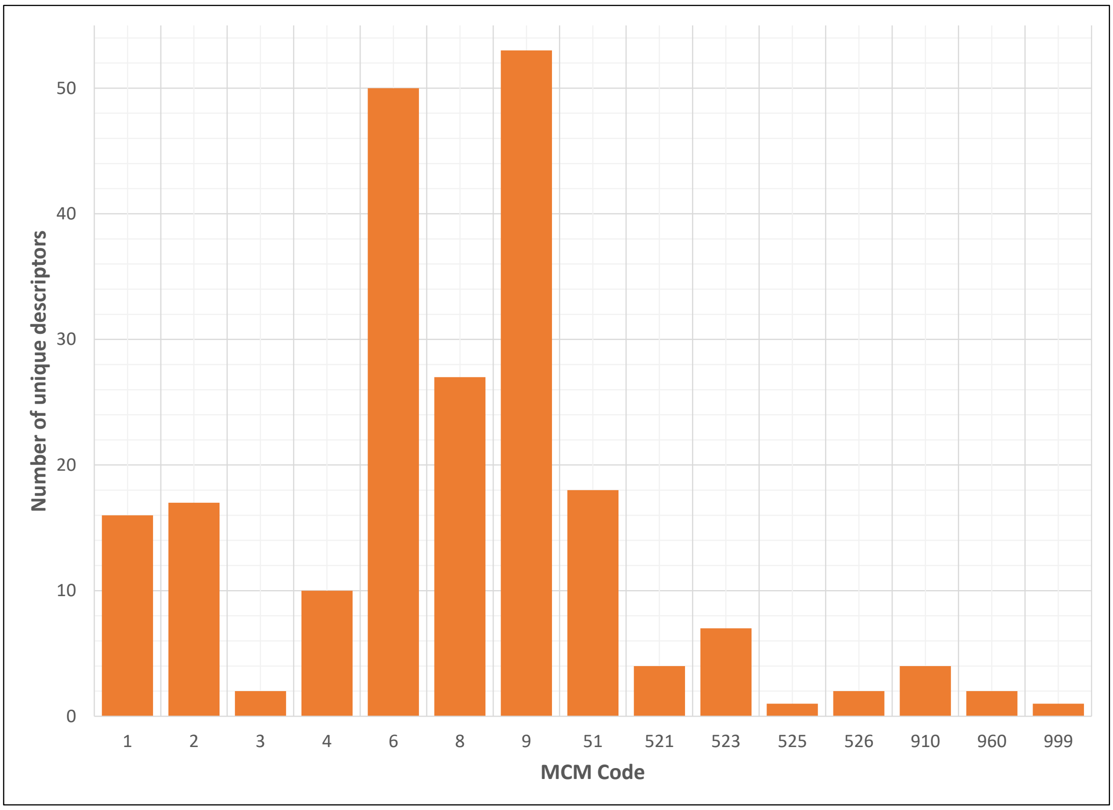



Figure 22 - Bristol Dataset MCM classifications

The range of possible textual descriptions within each MCM codes highlights that MCM codes can be treated as classes that various building types can fit within.

In contrast to the comprehensive NRD data, OpenStreetMap building data for the city of Bristol is comparatively limited comprising of just 45,089 infrastructures (just 17% of the NRD data). Figure 23 shows a side by side comparison of the spatial distribution of infrastructures within the two datasets. The OpenStreetMap data is comprised of 64 description types albeit the majority of features (85%) are not labelled. Figure 24 shows the percentage breakdown of the labelling used to describe features within the OpenStreetMap dataset.

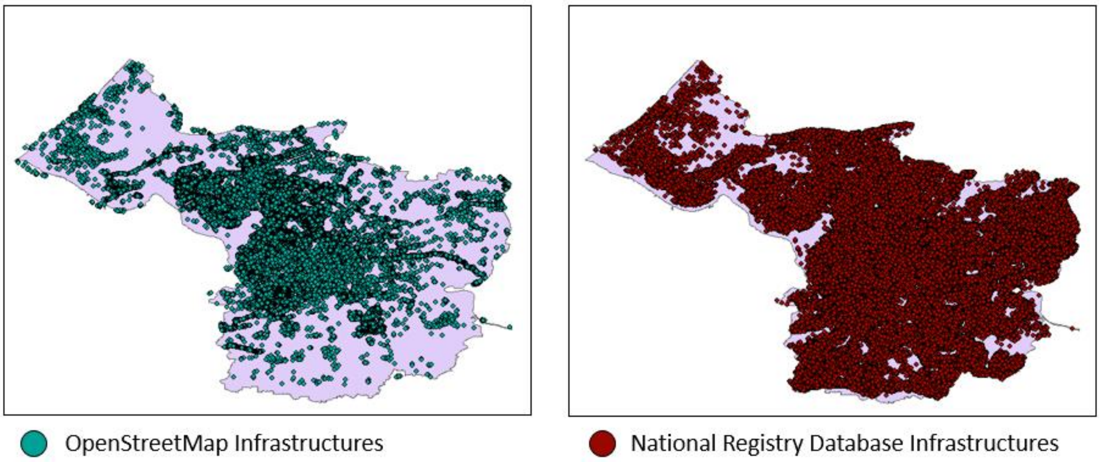



Figure 23 - Comparison of OpenStreetMap and National Receptor Dataset infrastructure distribution

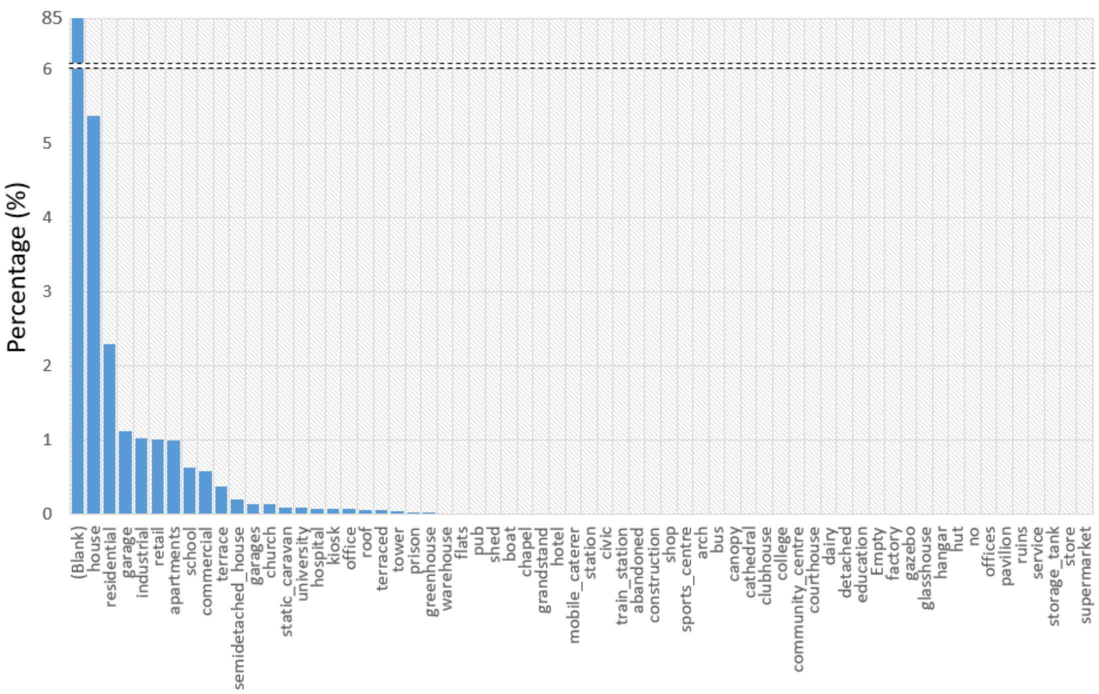



Figure 24 - Percentage breakdown of infrastructure types in OpenStreetMap data

To analyse the impacts of flooding events on infrastructures from data sources such as OpenStreeMap that do not have assigned MCM codes, these codes must first be defined. As shown in Figure 22 there are a range of possible description types for infrastructures that can be assigned an equivalent MCM code, therefore pre-processing of OpenStreetMap data or data from other sources such as directly gathered through local authorities can be carried out to assign appropriate depth-damage functions to individual infrastructures.

## 3.2.3 Flood indirect damage methodology and tool

Within a city, the impacts/effects of a flood event can not only result in direct losses due to physical damage of infrastructures, but also result in indirect losses due to the reduced functionality of the underlying systems in place that ensure the smooth running of a city.

### 3.2.3.1 Indirect tangible – Economic model

Previous work carried out by Cetaqua looked at the assessment of indirect tangible damages as a result of economic impacts. The methodology employed in this work was based upon previous works within CORFU, PREPARED and more recently adopted by the PEARL project and now subsequently will be built upon within RESCCUE to assess the indirect tangible damages.

Figure 25 shows the schema (from PEARL) that highlights the relationship between both direct and indirect damages and how the prior feeds into the latter. This approach is based on two loosely coupled independent (direct and indirect damage assessment) models. The "land use" characteristics already utilised within the direct damage assessment are also considered here as a means of defining parameters for the estimation of losses within an econometric model.

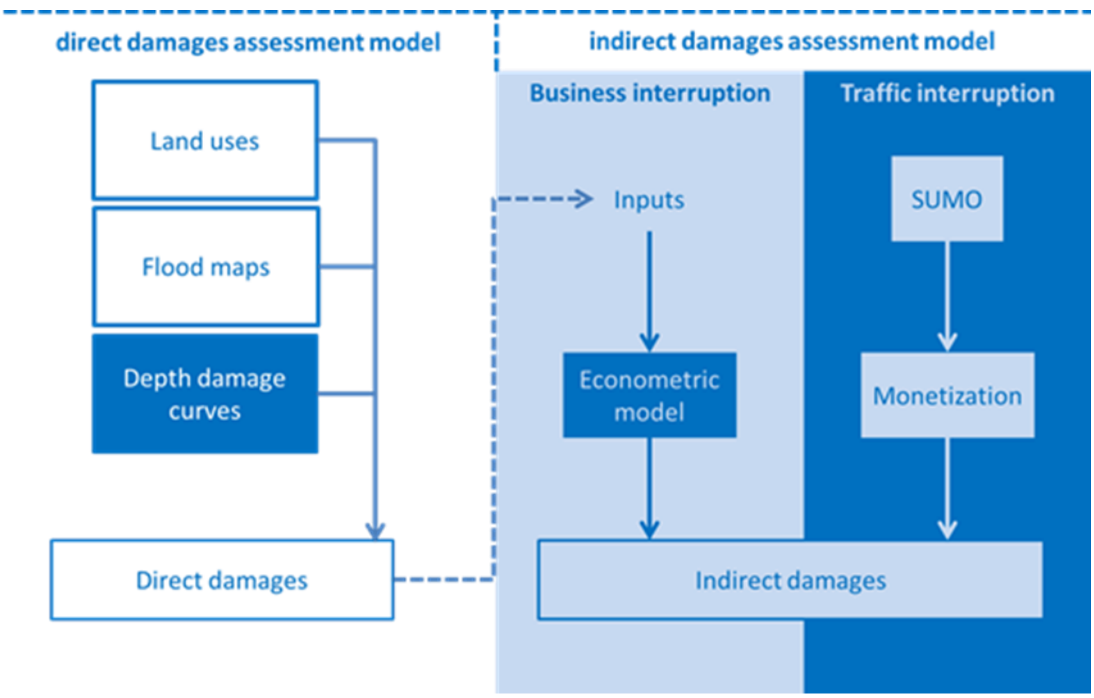



Figure 25 - Example of relationship between direct and indirect damage models (taken from PEARL)

The econometric model in PEARL calculated monetary losses as a result of business interruption (BI) which requires the following inputs: the land uses (i.e. commercial, industrial, residential…) and the direct damages allocation.

For the case of Marbella, within the PEARL project, the data for direct damages as a result of losses from numerous flood events were provided by the public reinsurer agency "Consorcio de Compensación de Seguros". This information from multiple events is utilised with the land-use and flood extent data as a means of calibrating the econometric model. The calibrated model can then estimate indirect losses as a result of flood events based upon direct damages.

The second part of the indirect damage assessment model is concerned with quantification of losses as a result of traffic disruption. Like that of the econometric model impacts on the traffic will utilise flood maps; in this instance however, the quantification of losses is not derived from land-uses but via changes in journey times and distances. Details of the approaches used in analysing traffic disruption are outlined in more detail in Section 3.3.

### 3.2.4 Summary of direct and indirect flood impact quantification methods to be employed in RESCCUE

Within the context of estimating impacts of flooding on buildings, contents, vehicles and indirect losses a number of means have been identified.

Table 8 - Approaches of flood impact quantification methods to be applied within RESCCUE

| Identified Impact Quantification Variable Summary | Applied RESCCUE methodology |
|---|---|
| Flood duration and depth | Utilising time-series depth-damage curve outputs. Both the duration and depths can be considered. In this regard the duration of flood waters impacting an infrastructure could be considered as a means of an amplification coefficient applied to the calculated losses from updated direct damage curves. |
| Spatial Resolution | When considering direct-damage losses, spatial resolution and grid cell alignments will be considered as a means of factoring in and quantifying some of the spatial uncertainties of the data. |
| Permeability and water ingress into buildings | Two potential methods can be utilised:<br><br>1. Using existing flood depth outputs and data (or assumptions) about internal building conditions and "Sealing Coefficients", water depths within buildings can be estimated and used a means of quantifying damage to building contents.<br><br>2. Utilising a combined multilayer *BCR* and *CRF* approach areas within the three studies will be examined to establish a comparative analysis flood-depth depths on the inside of buildings with respect to the outside to examine the implications on content damages. |
| Urban Growth | When examining flood model outputs from predicted future climate change scenarios, the probable changes to land-uses will also need to be considered. To take this into consideration, RESCCUE could look at potential urban growth futures and investigate how the predicted losses change based on these scenarios. |
| Indirect Damage | RESCCUE will follow suit of previous works from PEARL and CORFU in the derivation of indirect losses with respect to land-use classifications and direct damage assessment derived from updated depth-damage curves. |

## 3.3 Hazards and Impacts to Pedestrians and Vehicle mobility

The effects of climate change on the resilience of a city are not solely limited to fixed location infrastructures as a city's ability to function is also governed by the safety and the freedom of movement within and through it. The effects of flood based events can play a significant role in affecting movement throughout the city and the following sections within this document looks at ways in which these effects can be analysed.

## 3.3.1 Risks and Impacts of flooding on pedestrian and vehicular circulation in urban areas

### 3.3.1.1 Risk assessment for pedestrians

A consensus has been reached within the field of urban drainage and storm water management that hazard for pedestrians can be assessed taking into account two specific flow parameters: water depth (y) and velocity (v). In the studies by Russo *et al*. (2009; 2013) and of Eduardo Martínez-Gomariz *et al*. (2016) the most common flows during urban storm events, with low flow depth and high velocities, were reproduced through a physical model in real scale. These tests aimed to establish general hazard levels (low, medium or high) for pedestrians when attempting a street crossing under various combinations of water depth and velocity. This hazard classification would allow for threshold values to be established. Hydrodynamic conditions which result in a low hazard posed to pedestrians should be allowed to occur in the urban environment while medium and high hazard conditions should be more carefully considered and mitigated if possible. In the last experimental campaign carried out by Eduardo Martínez-Gomariz *et al*. (2016) a sample of 26 subjects were tested considering different conditions and exposure combinations (i.e. types of shoes, hands busy or free, and visibility conditions). The lower function threshold for all the assessed instability points is given by the product $(v \cdot y) = 0.22\ m^2 \cdot s^{-1}$. This study offers a revised and most updated stability threshold, which concentrates on acceptable levels when operating under low depth and high velocity conditions, the most common conditions in flooded streets during storm events. Also, new aspects such as the critical first step from a dry footpath into fast flowing water and the assessment of subjects' emotional response and perceptions have been considered in the hazard analysis.

The proposed limits for hazard delimitation are: Low Hazard below the product $(v \cdot y)=0.16 m^2 \cdot s^{-1}$, Medium Hazard for the values $(v \cdot y)$ compressed between $0.16\ m^2 \cdot s^{-1}$ and $0.22\ m^2 \cdot s\text{-}1$, and High Hazard beyond $(v \cdot y)=0.22\ m^2 \cdot s\text{-}1$. Furthermore, it has been considered that when the water depth exceeds 0.15 m, the hazard is high, no matter the product of velocity and water depth. Therefore, Low and Medium Hazard hydraulic conditions are both found below a water depth of 0.15 m. The maximum velocity that assure stability conditions for pedestrians, regardless the water depth, was established as $1.88\ m \cdot s^{-1}$. The hazard criteria is represented graphically in Figure 26.

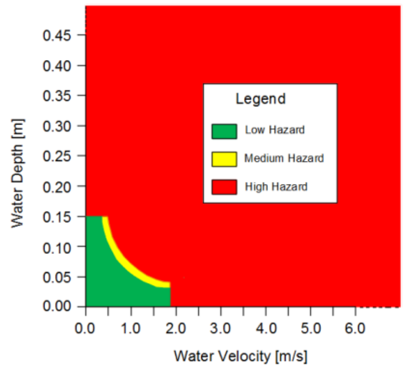



Figure 26 - Hazard criterion proposed based on the results of Russo et al. (2009; 2013) and Martínez-Gomariz et al. (2016)

Hazard maps (Figure 27) for different considered return periods may be produced by transforming depth and velocity variables, stored as outputs in each cell from the hydrodynamic model, into hazard levels.


Figure 27 - Example of a hazard map for Marbella Case Study for 1 (left) and 100 (right) years of return period. The high hazard corresponds with the colour red, medium hazard with yellow colour and low hazard with green colour

In order to assess the pedestrians' vulnerability, the methodology developed in CORFU project and reflected in D3.4 of that project (Hammond et al. 2015) will be followed. The Spanish National Institute of Statistics (Instituto Nacional de Estadística, INE), provides with statistical data of current population per census districts that will be used in the assessment. The required information per census district is the total inhabitants, people density, age and number of foreign people.

The next step on the methodology application is to set the thresholds that allow us to assess the vulnerability in each census area. Three thresholds will be defined according to the three indicators used (Table 9). First, the threshold for the people density was set using the medium density of the studied area of Barcelona and the definition of the National Institute of Statistics of urban area defined as a group of minimum 10 houses in a distance less than 200 m. Then, thresholds regarding the percentage of foreign people and the most vulnerable, people less than 15 years old and over 65, will be defined. The final vulnerability index was defined as the average value between the three indicators explained previously. The final vulnerability level was achieved according to the formulations proposed in Table 10.

Table 9 - Thresholds to assess human vulnerability according to different criteria

| Vulnerability index | C<br>% people age < 15 or > 65 years old | F<br>% of foreign people | D<br>People density |
|---|---|---|---|
| 1 (low) | ≤ 33% | ≤ 33% | ≤ 10 houses/200m |
| 2 (medium) | 33% < X ≤ 50% | 33% < X ≤ 50% | 10 houses/200m <X≤ average density in BCN |
| 3 (high) | > 50% | > 50% | > average density in BCN |

Table 10 - Formulation to compute the total vulnerability index

| Vulnerability level | Formulation |
|---|---|
| Low | (D+C+F)/3 < 1.5 |
| Medium | 1.5< (D+C+F)/3 < 2 |
| High | (D+C+F)/3 > 2 |

Following the criteria established above, the vulnerability map is produced per each census area involved in the research site (Figure 28).

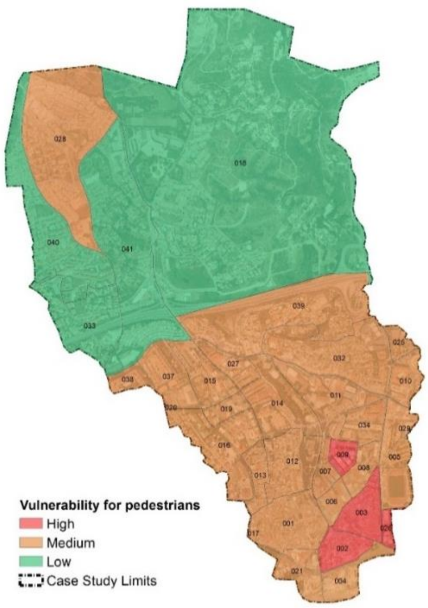



Figure 28 - Example of vulnerability maps for Marbella per census districts

In a context of climate change flooding and CSOs, problems can produce significant social and economic risks in urban and peri-urban areas. Methods for risk determination can be qualitative or quantitative, both having limitations. If risk is defined as the probability or threat to a hazard occurring in a vulnerable area, flood risk can be assessed through a risk map related to a determined scenario and return period by combining hazard and vulnerability maps (as shown in Figure 29). These maps can be used to evaluate potential impact on urban elements (i.e. pedestrians, vehicles, properties, etc.).

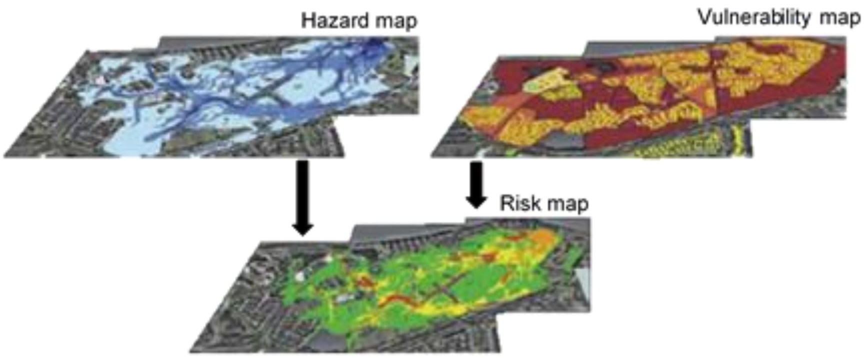



Figure 29 - Combination of hazard and vulnerability maps to produce a flood risk map

Qualitative assessment defines hazards and vulnerability and risk levels by significance levels such as "high", "medium" and "low" and evaluates the resultant level of risk against qualitative criteria. In this case, hazard and vulnerability maps are generally elaborated through specific criteria and indexes, so risk maps are created multiplying the vulnerability index (1, 2 or 3, corresponding to low, medium and high vulnerability) by the hazard index (1, 2 or 3, corresponding to low, medium and high hazard). Finally, the total risk varies from 1 to 9 where higher levels indicate higher risk. This approach can be summarized in the following risk matrix shown in Figure 30 and the risks then visualised for different return periods (Figure 31).

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

Figure 30 - Risk matrix obtained by multiplying vulnerability and hazard indexes


Figure 31 - Example of risk maps obtained for Marbella case study for 1 (left) and 100 (right) return period

### 3.3.1.2 Risk assessment to Vehicles

A risk assessment for vehicles will be conducted based on the same procedure proposed to pedestrian risk assessment. A preliminary hazard and vulnerability analysis will be carried out to finally apply the risk matrix and perform risk maps for different return periods. The hazard analysis will be based on vehicles stability criteria and vulnerability based on vehicular flow intensity.

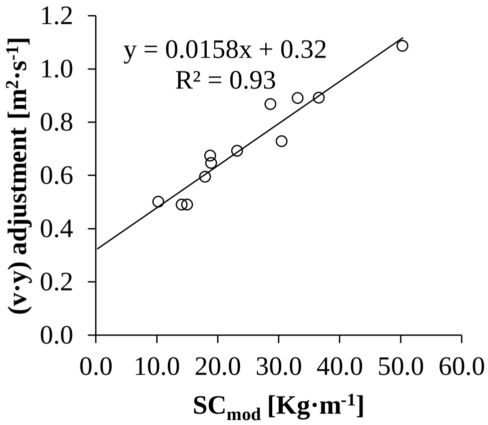
When a vehicle is exposed to flooding, in case of losing stability, it becomes buoyant and may be washed away with potential injuries and fatalities. Therefore, the analysis of the stability of vehicles exposed to flooding is important in order to make decisions to reduce the damages and hazards. In the research of Martínez-Gomariz *et al*. (2017), based on the experimental campaign that included a range twelve car models, a new methodology to obtain the stability threshold for any real vehicle exposed to flooding was developed. The experiments were conducted with three different model scales (1:14, 1:18 and 1:24) and involved analysis of both friction and buoyancy effects, which made this the most comprehensive research study to date in this regard. This methodology enables to define a stable area in the domain flow depth-velocity with sufficient accuracy for any real vehicle. In this sense, a tool is provided which decision-makers in the field of urban flood risk management can employ by defining a design vehicle and obtaining its corresponding stability threshold.

Previous experimental studies regarding stability of vehicles exposed to flooding were reviewed in E Martínez-Gomariz *et al*. (2016) and it was found that no study included a test with more than two or three scale model vehicles; therefore it was not possible to develop a general methodology for any real vehicle. The AR&R criterion (Shand *et al*. 2011) was the most accurate reference before Martínez-Gomariz *et al*. (2017) studies to guarantee the stability of vehicles according to three types of vehicles. The Australian criterion was updated and validated in E Martínez-Gomariz *et al*. (2016) with the results of subsequent studies. Nevertheless, the proposed criterion is not flexible enough to consider any vehicle with different characteristics.

The methodology proposed in Martínez-Gomariz *et al*. (2017) study enables to define a stable area in the flow depth-velocity domain with sufficient accuracy for any real vehicle (Figure 32), just by calculating a vehicle stability coefficient [9].

$$SC_{mod} = \frac{GC \cdot M_c}{PA} \cdot \mu \qquad [9]$$

where GC is the ground clearance, $M_c$ is the kerb weight, PA is the plan area and μ is the friction coefficient between tyre and ground. In this sense, an appropriate vehicle for a study area can be selected and by obtaining its corresponding stability threshold to define a hazard criterion for vehicles.



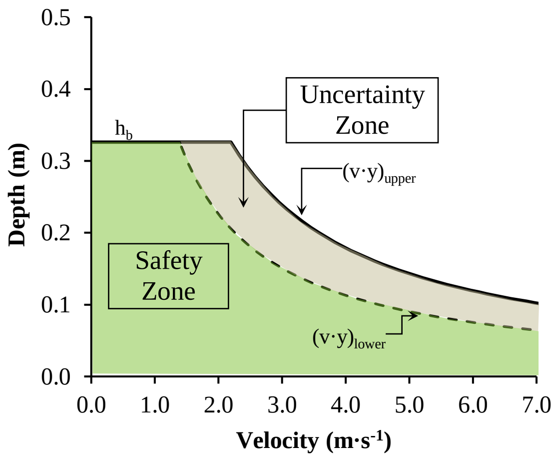




Figure 32. Scatterplot and lineal adjustment of $(v \cdot y)_{fit}$ and $SC_{mod}$ values for each tested scale model vehicle (left) and definition of the proposed methodology in Martínez-Gomariz *et al*. (2017)

In order to define the stability threshold fully, theoretic buoyancy depth can be calculated by the expression [10]. The derivation of this equation responds to the same criterion conducted to verify the results of experimental buoyancy tests, which was demonstrated to be accurate.

$$h_b = \frac{M_c}{\rho_w \cdot l_c \cdot b_c} + GC \qquad [10]$$

where $h_b$ is the buoyancy depth, $M_c$ is the weight of the vehicle, $\rho_w$ is the water density, $l_c$ is the length of the vehicle, $b_c$ is the width of the vehicle and GC is the ground clearance of the vehicle.

According to an article published in La Vanguardia (Spanish newspaper) on 3rd of September 2015, the two most sold vehicles in Spain are Citroen C4 ($SC_{mod}$: 5.90 kg·m$^{-1}$), Seat Leon ($SC_{mod}$: 6.02 kg·m$^{-1}$) and Seat Ibiza ($SC_{mod}$: 4.81 kg·m$^{-1}$). Therefore the proposed vehicle for the Spanish Case Study (Barcelona) will be the Seat Ibiza model due its lowest $SC_{mod}$ value, which was calculated considering a friction coefficient of 0.25. The Seat Ibiza model stability threshold, according to the methodology proposed by Martínez-Gomariz *et al*. (2017), is $(v \cdot y)_{lower}$= 0.40 m$^2$·s$^{-1}$ and presents a buoyancy depth of 28 cm. In order to define the hazard limits, a new $(v \cdot y)_{upper}$ value is proposed based on the maximum friction coefficient (μ=0.75) proposed in Gerard (2006). That friction coefficient value yields a $SC_{mod}$= 14.43 kg·m$^{-1}$, and therefore an stability threshold $(v \cdot y)_{upper}$= 0.55 m$^2$·s$^{-1}$. Thus, the proposed limits for hazard delimitation are: Low Hazard below the product (v·y)=0.40 m$^2$·s$^{-1}$, Medium Hazard for the values (v·y) compressed between 0.40 m$^2$·s$^{-1}$ and 0.55 m$^2$·s$^{-1}$, and High Hazard beyond (v·y)=0.55 m$^2$·s$^{-1}$ (Figure 33). An analogous procedure will be conducted in order to select a representative vehicle in each RESCCUE site (Lisbon and Bristol).

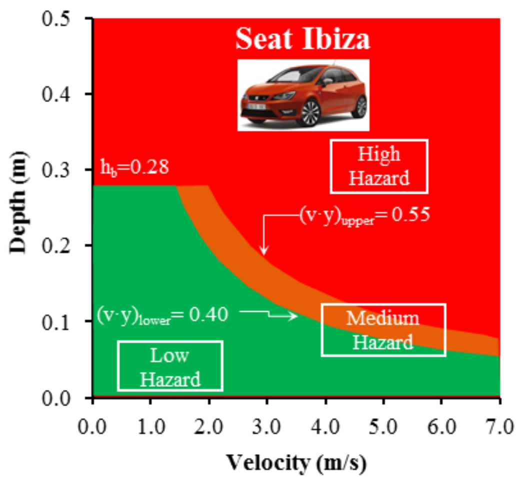



Figure 33. Hazards levels proposed for vehicles based on the results of Martínez-Gomariz *et al*. (2017)

In order to assess the vehicles vulnerability, three levels can be proposed based on vehicular flow intensity of the different areas with road traffic. The more traffic flows the more vulnerable is this road. Table 11 indicates three vulnerability levels as an example. Ultimate limits could be defined further on.

Table 11. Vulnerability levels used in CORFU project based on vehicular flow intensity

| Vulnerability Level | Vehicular Flow Intensity (VFI) |
|---|---|
| Low | VFI < 5000 |
| Medium | 5000 ≥ VFI ≤ 10000 |
| High | VFI > 10000 |

Following this criterion, a vulnerability map could be performed and by crossing hazard and vulnerability information risk maps for vehicles could be developed for each research site (Barcelona, Lisbon and Bristol).

### 3.3.1.3 Vehicle damage curves

In the cities there is a great diversity of vehicles, being the cars the ones that predominate. During a flood event these can be dragged, overturned or can even float and move with the flow of water. The instability of vehicles has been studied by different authors (E Martínez-Gomariz et al. 2016). However, vehicles, even if they do not reach the stability limit, will receive the impact of the flood, resulting in economic costs that cannot be neglected. In this sense, damage curves associated with vehicles can be presented, with the same criteria as for buildings, in order to find the damages to the vehicle as a function of the water depth. This approach is found in the literature although it is a less mature research than damage curves for buildings and has been carried out by a small number of authors. Only three developments have been found within the bibliography. The approaches, that are summarized in Table 12, are those proposed in the HAZUS-MH model developed by the US (Federal Emergency Management Agency (FEMA) 2015), the criteria proposed in the CRUE project (Francés *et al.* 2008) and, finally, the one proposed by the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers 2009b).

Table 12 - Summary of the depth damages curves identified in the state of the art review (Martínez-Gomariz 2016)

| Ref. | Model | Country | Development | Damage | Types of vehicles | Initial Cost | Analysis Approach |
|---|---|---|---|---|---|---|---|
| (FEMA, 2015; Scawthorn et al., 2006) | HAZUS-MH (FEMA) | EEUU | Synthetic | Relative (%) | Car<br>Light Truck<br>Heavy Truck | New or used applying 50% of new one price | Individual Objects |
| (Francés et al. 2008) | CRUE | Spain | Synthetic | Absolute (€) | Gasoline<br>Diesel<br>Averaged | No specified | Individual objects every 100 m2 affected |
| (USACE, 2009) | USACE | EEUU | Empirical-Synthetic | Relative (%) | Sedan<br>Pickup Truck<br>SUV<br>Sports Car<br>Mini Van | Market value | Individual Objects |

After a previous analysis of the approaches for the three damage curves found, it is observed that the level of completeness and accuracy are quite different between them. The USACE proposal is the most current research and all the steps for the development of the damage curves are comprehensively described. For those reasons, together with the availability of damage curves for five types of vehicles, these curves were considered the most adequate to be adopted in the RESCCUE project. On the other hand, the fact of the damage being expressed as a percentage makes that these curves can be transferred and applicable to other countries, taking into account the local price of vehicles.

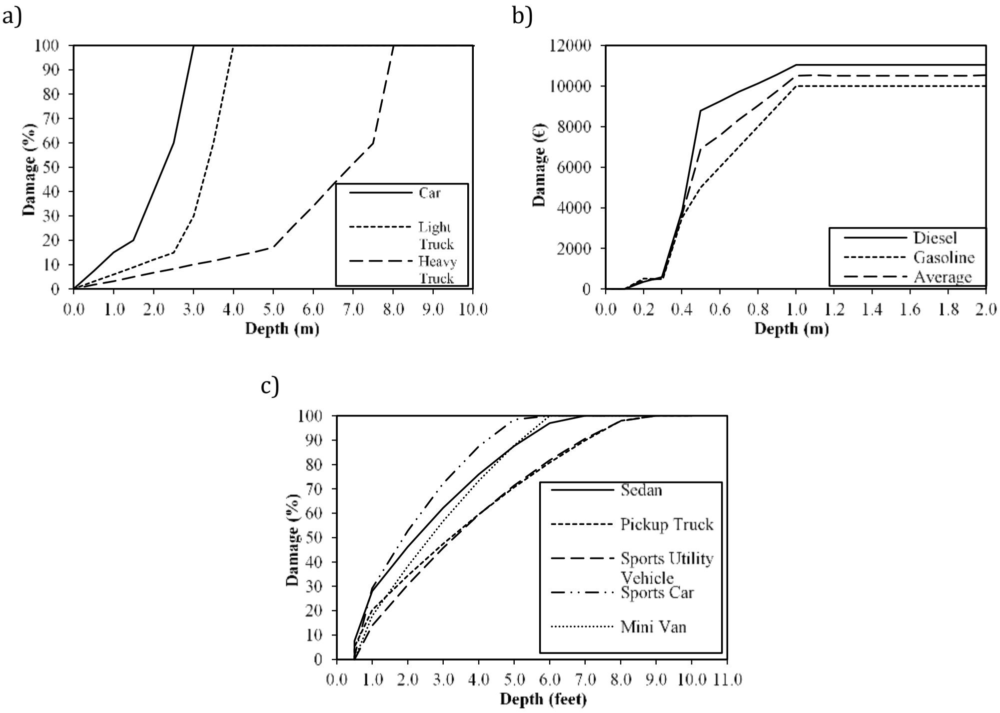



Figure 34 - Depth damage curves per type of vehicle proposed in a) HAZUS-MH, b) CRUE project, and c) USACE

The US Army Corps of Engineers (USACE) conducted a specific study for the development of damage curves for vehicles exposed to flooding. This study is reported as a Memorandum: Economic Guidance Memorandum, 09-04, Generic Depth-Damage Relationships for Vehicles (U.S. Army Corps of Engineers 2009b). The USACE's Water Resources Institute's "Flood Damage Data Collection Program" collects information from past floods in order to produce reliable estimations on economic damages due to flood events. As part of the surveys carried out to determine the effects of flooding on residential properties, data were also collected on the damage caused to vehicles parked in such dwellings for the ten communities that suffered the greatest floods. The baseline information for the development of such curves (Figure 34) was therefore the data provided by the affected owners in relation to the estimation of the vehicle, the damage suffered and the depth of water that affected the vehicle. Damage curves were developed for five vehicle types from a sample of 640 vehicles. Such data were processed statistically to construct such curves by regression analysis.

Ultimately, the purpose of the memorandum is to provide guidelines for the generic use of damage curves developed for flood risk management studies requested by the USACE. These curves will be normally used in studies for urban flooding since in rural areas the density of vehicles is not considerable.

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

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

The number of vehicles present within transportation network within a city operates and varies in both space and time. The temporal aspect of a transportation model relates to that the number of journeys/vehicles present within the road network during a 24 hour period varies with the prospect of peak hours in mornings and evenings due to work and school runs. To accurately achieve an understanding of the potential impacts of flood events, the spatial and temporal aspects of a flood model needs to be integrated with the traffic model used within the city.

## 3.3.2 Overview of city's transport models

### 3.3.2.1 Lisbon

The city of Lisbon looks at its traffic control at both meso and microscale levels. A small part in the core region of the city is managed by an intelligent traffic control system called "GERTRUDES"[3] whereas the rest of the city is unmanaged.

### 3.3.2.2 Bristol

For the city of Bristol there is a Paramics traffic model for the city centre which is a microsimulation though it is not linked to the real-time data that is obtained via the SCOOT[4] system in place and the array of cameras at key locations throughout the city. VISSIM[5] is used

[3] http://www.gertrude.fr/
[4] http://www.scoot-utc.com/
[5] http://vision-traffic.ptvgroup.com/en-us/home/

in the northern part of the city for the A4018 region. In addition to these for the west of England there exists a multi-model strategic model SATURN[6]/EMME[7] whereby potential Origin-Destination matrices could be extracted.

#### 3.3.2.3 Barcelona

Within Barcelona the traffic modelling is carried out via the use of TransCAD®[8] software (Figure 35) that is designed for storing, displaying, managing, and analysing transportation data. The tool itself facilitates the inclusion of origin destination matrices and is configured temporally over 24 hour period therefore allowing for a detailed analysis of variances of traffic flow throughout the day.

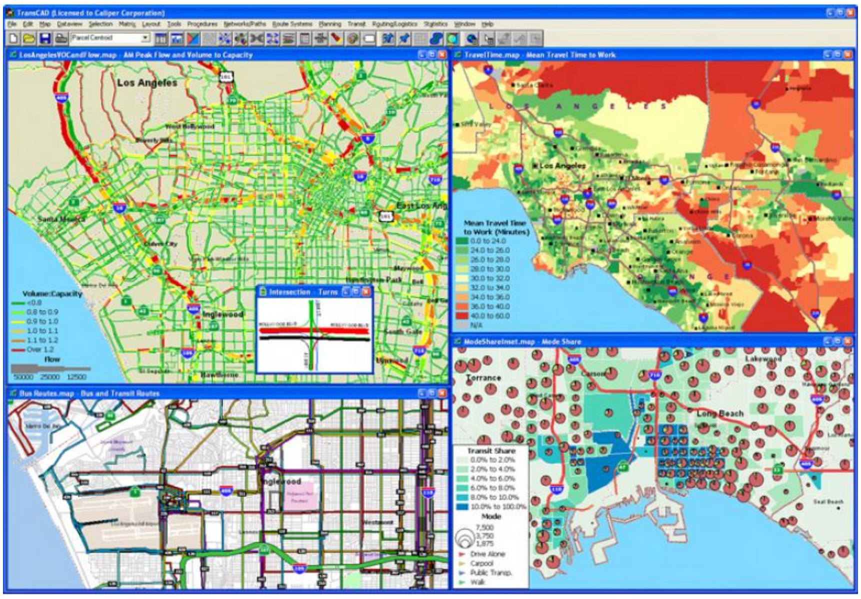



Figure 35 – TransCAD® software interface

### 3.3.3 Real-time monitoring

Each of the RESCCUE cities have in place systems for the real-time monitoring and traffic counting within regions of their cities. This monitoring is carried out within specifically designed aforementioned software packages GERTRUDES and SCOOT.

The primary functions of these packages is to control traffic signals in an urban areas in order to optimise traffic flow within those areas. Detectors embedded within the roads can provide real-time information of traffic flow (numbers and speed) along specific routes within the network. Figure 36 shows how the analysis of sensors within the SCOOT system predict build-up of traffic within a link on a network. Here, when vehicles pass a detector within a link the

[6] https://saturnsoftware2.co.uk/
[7] https://www.inrosoftware.com/en/products/emme/
[8] http://www.caliper.com/tcovu.htm

information is sent to the SCOOT system that creates a “cyclic flow profile” for that link. The “Red time” and “Green time” respectively in Figure 36 depicts the traffic signal state along that link when vehicles will arrive at the stopline at normal cruising speed; during the green state cars discharge from the stopline at a validated saturation rate. Analysing data from multiple links throughout the network it is possible to predict flow rates across the network and optimize the network through traffic signaling control to reduce wasted green time at intersections.

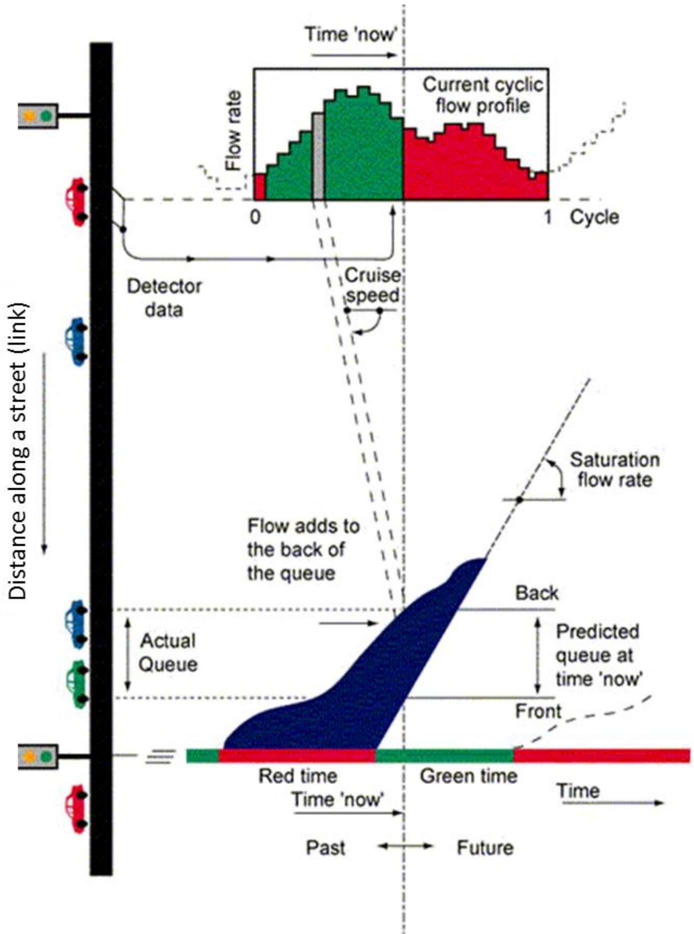



Figure 36 - How SCOOT works (http://www.scoot-utc.com/DetailedHowSCOOTWorks.php?menu=Technical)

Simulating traffic control to a high spatial degree on a vehicular level provides an effective means of real-time optimised traffic management. Information gained about this normal time-variant day to day traffic flow can be used to provide a baseline for traffic flow in abnormal conditions such as those during extreme weather events like snowfall and flooding where the characteristics of traffic flow along links will change either via reducing safe driving speed limits (time taken to travel through a link) or by road closures that result in diversion of traffic causing an increase in vehicle saturation on other links. For these sort of scenarios micro and meso-scale traffic models linked with climate model outputs can be employed to estimate the possible impacts.

### 3.3.4 Micro-scale modelling approach

Previous work within PEARL looked at the integration of a microscopic traffic model SUMO (Simulation of Urban Mobility) to simulate the movement of individual vehicles within the transportation network with data outputted from flood models. Simulating traffic flow at this level allows for the possibility of closure of individual and/or multiple roads and the analysis of traffic flow via alternative routes. The software also facilitates the use of closing roads for specific vehicle types under certain conditions therefore roads can be closed for general public but still accessible by emergency vehicles.

The micro-simulation approach simulates traffic flow down to individual journeys i.e. at a car by car level and also facilitates the inclusion of public transport, bicycles, pedestrians and even emergency vehicles. The configuration of SUMO requires the following basic inputs:

1. Road network
2. Speed limits
3. Traffic lights
4. Traffic quantity

With this level of basic information the workings of a traffic model begin to form where in the initial instance the traffic flow can be randomly generated. The traffic model can be expanded upon further by substituting the random traffic flow with realistic traffic flow based on origin destination matrices such as the inclusion of work and school runs.

Figure 37 shows the methodology employed by Pyatkova *et al*. (2015) of linking flood model data to the micro-scale traffic simulation data.

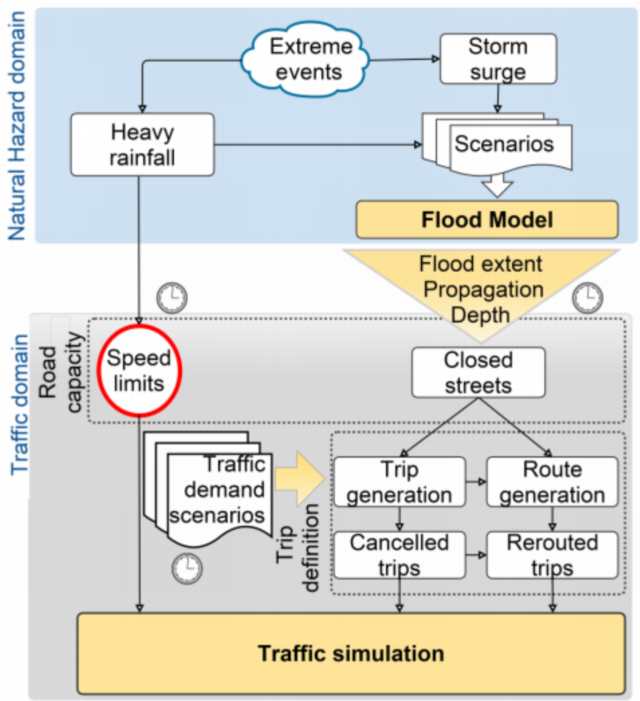



Figure 37 - Methodology of linking traffic simulations with Flood Models proposed in PEARL project (Pyatkova et al. 2015)

When analysing and quantifying the impacts of flood events on traffic the approach to be employed within RESCCUE will be based upon that developed within the PEARL project that looked at three vectors: ***increase in pollution*, *increase of fuel consumption*** *and an in* ***increase in vehicle journey time***.

### 3.3.4.1 Journey time increase

For the micro-scale modelling as is in the use case of Bristol, Open Street Map data will be utilised (in part) within SUMO to depict the road layout (Figure 38). The OSM data contains detailed information about the road network, road types, road speeds, junctions and traffic signals; all of which can be referenced via SUMO. This information facilitates the production of a working micro-scale traffic model of the city that can then be coupled with a flood model to analyse the effect flood based events will have on the network.

Within SUMO realistic journey scenarios that depict rush hours (school runs, work runs etc.) can be created to get both a temporal and spatial distribution of traffic within the city. As this simulates traffic at the individual vehicular level, distinctions between private and public transport can also be analysed. This traffic data is then linked with flood model outputs that will change parameters (speed limits) of the roads within the network and/or close roads at certain sections for specified periods of time. Spatial and temporal information about flood extents is used to define road parameters (open, closed, reduced speed capacity) in both space and time and the overall performance of the network will be evaluated.

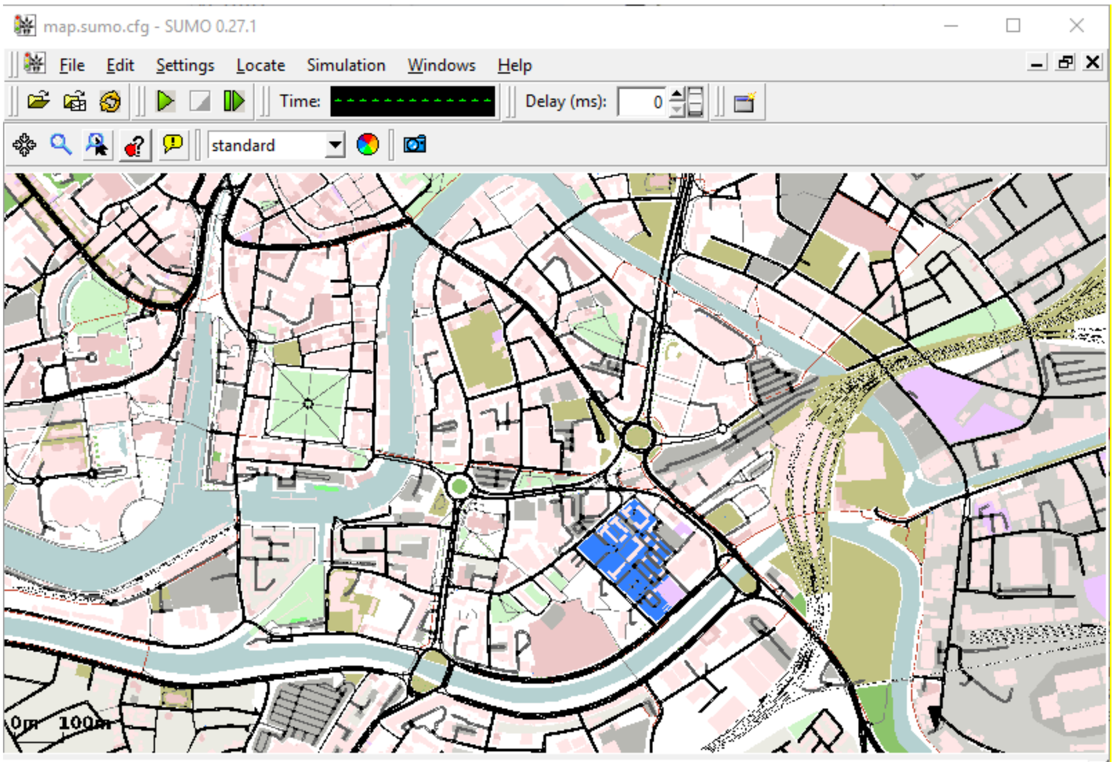



Figure 38 - OSM data of Bristol Temple Meads within SUMO GUI

### 3.3.4.2 Pollution increase

The effect of Greenhouse Gases (GHG) and Climate Change are an important challenge right now and the studies of their impacts in the economy are increasing. It is also clear that these impacts in the economy increase over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater Climate Change impact (IWGSCC 2013). Thus, the first impact to be monetized is the pollution increase between the normal traffic situation and the situation in case of flood. The increase in pollution is directly related to the journey time of vehicles within the network, and therefore, can be expressed accordingly. The increase in pollution is not solely, however, linked to the journey time but also tied in to the vehicle type. One of the advantages of micro-scale simulations is that you simulate down to an individual vehicular level therefore the impact on specific classes of vehicles can be analysed to examine their contributions to pollution increases.

### 3.3.4.3 Fuel consumption

There are numerous variables that could be considered with regards to fuel consumption. In the scope of the research within RESCCUE the fuel consumption primarily follows the changes in journey time and distance. Like that outlined in the pollution case, the vehicular type also plays a role in this instance and can be analysed.

## 3.3.5 Meso-scale modelling approach

The model as used by Barcelona (and potentially to be employed in Lisbon) utilises a meso-scale model as opposed to a micro-scale approach whereby traffic flow is not modelled at an individual vehicle level where instead it is represented as flow value across a link within the network. A “link” in this instance refers to a section of the road network between two junctions. Figure 39 shows the road network layout for the city of Barcelona where information about the traffic flow is stored at a link level whereby information relating to traffic flow between these links is stored within a database and can be analysed to evaluate the performance of the road network.

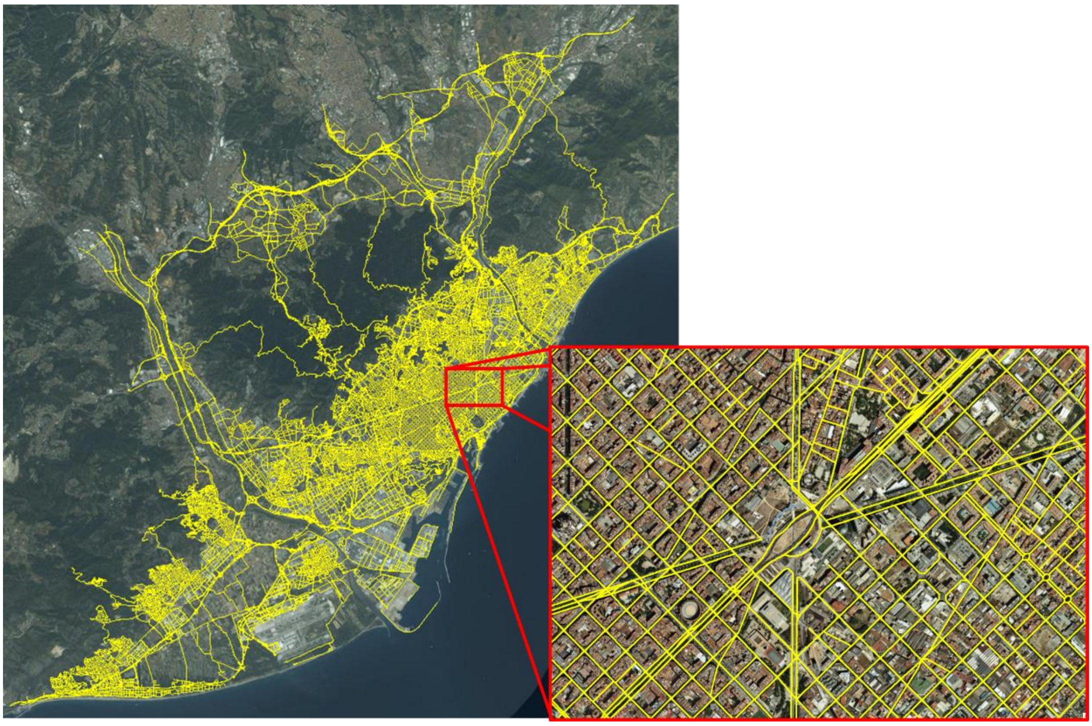


Figure 39 - Road network map for Barcelona

### 3.3.5.1 Analysing impacts at a meso-scale

The Bureau of Public Roads (BPR) have developed a link-congestion (or volume-delay, or link performance) function $S_a(v_a)$ for analysing road networks. Equation 11 shows how this function per unit time where:

$S_a(v_a)$ = average travel time for vehicle on link $a$
$t_a$ = free flow travel time on $a$ link a per unit time,
$v_a$ = volume of traffic on a link $a$ per unit time (or more accurately: flow attempting to use link
$c_a$ = capacity of link $a$ per unit of time
$\alpha$ = speed factor parameter that represents speed and free-flow speed at capacity
$\beta$ controls slope of the curve of the volume to capacity ratio

$$S_a(v_a) = t_a . \left[1 + \alpha \left[\frac{v_a}{C_a}\right]^{\beta}\right] \tag{11}$$

There are a range of alpha and beta values that can be applied to certain road types.

Table 13 from Cambridge Systematics Inc. (2016) shows the range of BPR values used for freeways and arterial roads.

Table 13 – Range of BPR Function Parameters

| | Minimum | Maximum | Average |
|---|---|---|---|
| **Freeways** | | | |
| $\alpha$ | 0.1 | 1.2 | 0.48 |
| $\beta$ | 4.0 | 9.0 | 6.95 |
| **Arterials** | | | |
| $\alpha$ | 0.15 | 1.0 | 0.53 |
| $\beta$ | 2.0 | 6.0 | 4.4 |

Like the approach outlined earlier in the micro-scale traffic modelling (Figure 37) spatial and temporal analysis of the flood models can be utilised as a means of modifying the components of equation 11 along impacted links within the road network. These new parameters can then be re-incorporated into TransCAD® and its effects analysed.

### 3.3.6 Summary of Hazard and Impact Quantification methods to be applied to city mobility models in RESCCUE

Flood model outputs vary both spatially and temporally. Outputs from these models can be overlaid onto road network data to define their impacts both in space and time. The impacts of flooding can either reduce capacity of the road via reduction of safe traffic flow speeds or result in road closures due to water depths on road being unsurpassable to vehicles.

Although the primary focus of impacts on traffic models in RESCCUE are flood based, any impact that can result in the closure of reduced capacity of roads such as snowfall, high winds across bridges, land subsidence etc. could theoretically be applied in a similar manner.

The major difficulties in establishing a methodology for assessing impacts on traffic flows within the three study areas are related to the difficulty in obtaining accurate or distributable traffic data and that the software used via the cities are commercial based. However, the spatial distribution of road networks within each city are obtainable along with spatially distributed time-series flood inundation data from model outputs. The plan therefore that can be universally transferred to each city would be to create a meso-style “resistance to flow” map whereby a weighted traffic disruption (resistance to flow) value can be obtained at a “link” level for each road network. These spatially and temporarily variant resistance map outputs can then be utilised as a means of adjusting parameters within pre-existing meso and micro traffic models employed by each city.

In the quantification of impacts as a result of flooding disruption the proposal therefore is to pursue the work previously done within PEARL further by looking into micro-scale of traffic flow for the city of Bristol to coincide with their previously used model and additionally meso-scale models for all cities. Table 14 provides a brief summary as to the methods used for quantifying level of impacts on traffic as a result of a flood event or road closure.

Table 14 - Quantifying Impacts on mobility within cities

| **Impacts on traffic modelling parameter** | **Scale** | **Cities** | **RESCCUE** |
|---|---|---|---|
| Journey time increase | Micro | Bristol | Information about changes of road properties as a result of flood events can be fed into the micro-scale traffic simulation software and the changes in journey times can be analysed |
| | Meso | All | For the meso-scale model, the coefficients that define average journey time along links within a network will be altered accordingly based on information fed back from micro-scale modelling. |
| Pollution increase | Micro | Bristol | Pollution increase analysis is determined via analysis of increases in journey times along the road network as a result of flood events |
| | Meso | All | |
| Fuel Consumption | Micro | Bristol | Fuel consumption changes are derived via examination of journey/route changes required |
| | Meso | All | |
| Public Transport Disruption | Micro | Bristol | The disruption caused to public transport within each city as a result of road closures or reduced traffic flow capacity will be analysed. |
| | Meso | All | |

In addition to traffic modelling, the risks of surface flow posed to both pedestrians and vehicles will be analysed along with the quantification of monetary losses as a result of vehicle damage during flood events based on works by Russo *et al*. (2009; 2013) and Martínez-Gomariz *et al.* (2016). Whereas previous analyses of impacts focused on depths in these instances the flow velocities are considered. Table 15 provides a summary of methods that will be used in the quantification of these risks.

Table 15 – Quantifying risks and impacts to pedestrians and vehicles

| | |
|---|---|
| Risk to Pedestrians | Based on work by Russo *et al*. (2009; 2013) and Martínez-Gomariz *et al.* (2016) water depths and velocity output maps will be used to examine spatial distribution of risks posed to pedestrians from simulated flooding events |
| Risk to Vehicles | Like that of the risks posed to pedestrians, depth velocity curves will be utilised to examine spatial distribution of risks to vehicles as a result of flooding events. |
| Vehicular Depth-Damage curves | Information relating to traffic flows, locations of car sales areas, and potential parking of vehicles within residential, business, industrial and commercial areas estimates on vehicular density in both space and time will be obtained and/or derived for each city. Information about vehicle distribution will be coupled with flood model outputs and via the use of depth damage curve data estimated impacts/losses will be derived. |

## 3.4 Quantifying Impacts/Disruption to Waste sectors

Climate driven events such as high winds or flooding can directly lead to the displacement of both waste and waste containers within a city. If the displaced waste material is to get into the drainage network, it could potentially affect/reduce the performance of said network that increases the city's susceptibility to flooding in future climate scenarios.

Barcelona has an extensive municipal service for a daily collection of household and commercial waste to provide waste collection to citizens and ensure a clean and healthy public space. This service is carried out through 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 Dots. 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 by recycling it, 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 fraction-types of containers. There are containers for each one of them located citywide in order to make waste management easier: tins, glass, paper and cardboard, organic and remains. All citizens have recycling collection containers located less than 100 meters from their home. When an urban flood occurs those containers may lose their stability, thereby allowing debris (i.e. solid waste contained) and leachate to escape from the container and contaminate the flood water. Also the container itself may be washed away (i.e. a massive debris) together or separately with its content (Figure 40).

Figure 40 - Real container instabilities due to flooding in Barcelona

An analysis of the potential behaviour of containers against floods in Barcelona caused by historical and low and medium return-period design storms (i.e. 2, 5 and 10 years) will be conducted. A large dataset on the spatial distribution and contents of waste bins throughout the city has been acquired (Figure 41) for cross-referenced with flood data. The different modes of instabilities (Figure 42) when exposed to flooding will be studied and stability thresholds is proposed.

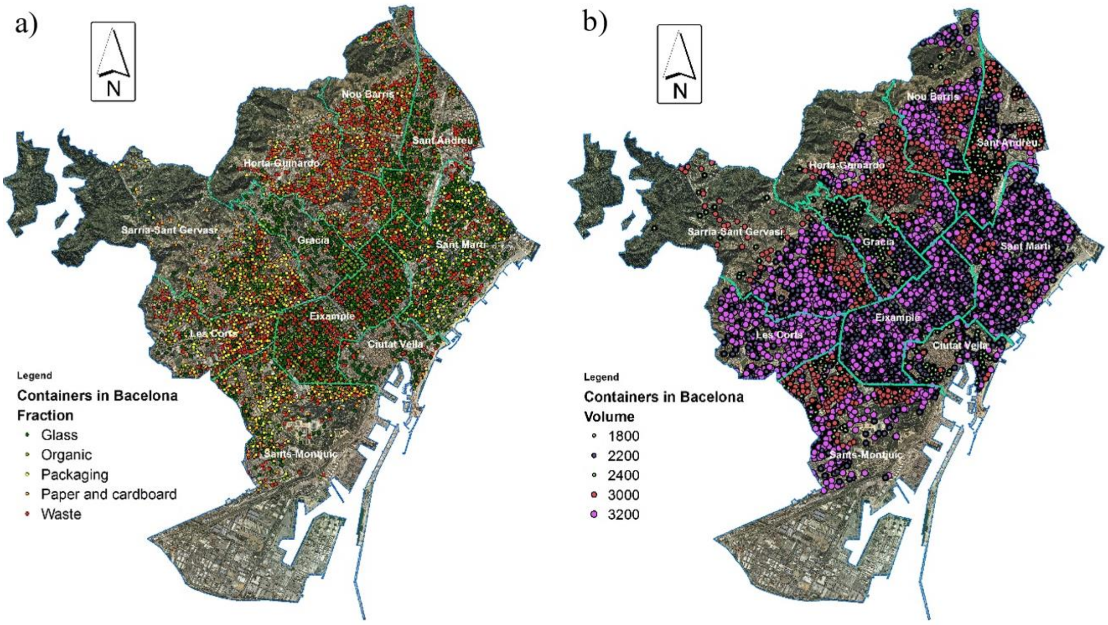



Figure 41 - Containers distribution in Barcelona classified according to a) Fraction type, and b) Volume

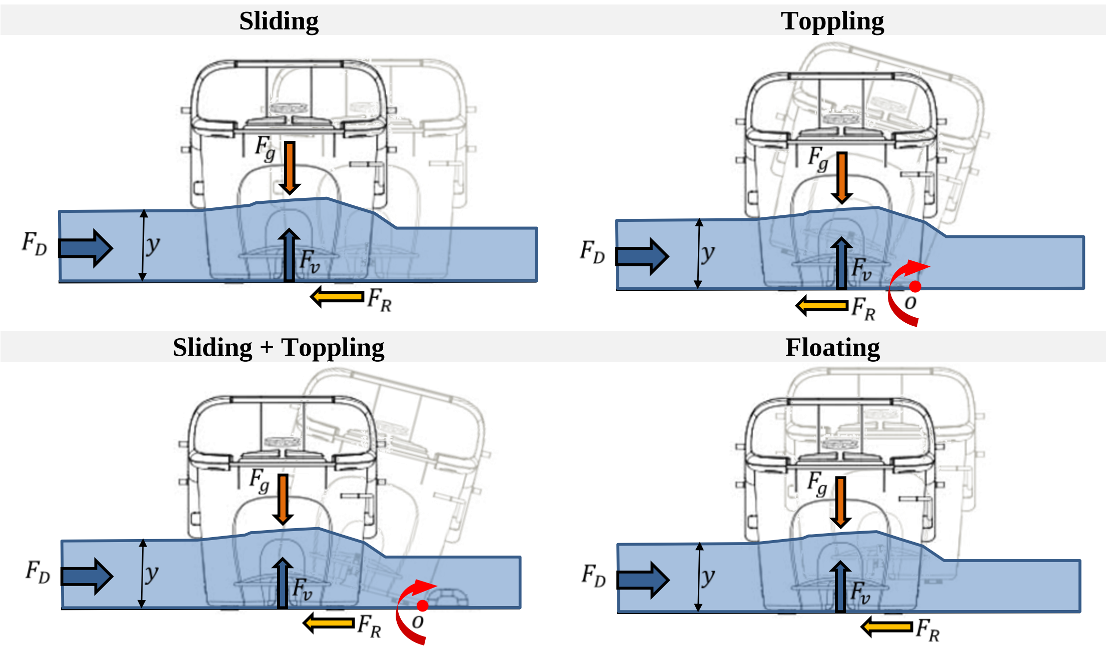



Figure 42 - Different modes of instability for a flooded container

### 3.4.1 Summary of Impact Quantification methods to be applied to waste sector

Linking of flood model outputs that comprise of both flood depth and flood water velocities will be overlaid with spatial data to quantify the risks/likelihood of waste disposable containers being toppled over during a flood event.

Table 16 - Assessing impacts on waste sector

| Impact Type | RESCCUE approach |
|---|---|
| Tangible indirect impacts | Damage and disruption estimates based on estimated clean-up costs |
| Intangible impacts | Effects of increased contamination and public perception |

## 3.5 **Other hazard and quantification impacts on Urban Water Cycle**

### 3.5.1 Water distribution systems

One of the major risks to water distributions systems is that of pipe burst events resulting in both loss of supply to receivers and also posing risks of flood based events. There are numerous potential causes to pipe burst failure, some relating to physical condition of the network, accidental damage during construction and climate driven events. In the work flow within RESCCUE the method used to analyse the effects of pipe burst scenarios will look at quantifying the disruption of supply and the impact of flooding as a consequence of the pipe burst event.

Where data is available stresses on the pipe network, highlighting regions of likely pipe burst scenarios can be identified. This can be achieved spatially through analysis of climate driven events such as freeze/thaw cycles and periods of drought in conjunction with their effects on various soil types beneath the respective cities as soil shrinkage and expansion varies depending on composition and thus leads to land shifts and put additional stressed on the network resulting in pipe burst event (Wols & van Thienen 2016).

Using regions where weaknesses in the pipe network are identified as reference, flood modelling software such as CADDIES 2D[9] will be used to simulate multiple burst location events. Results from analysis using this approach can be utilised to estimate likely damage estimates using flood depth data along with impact assessment methods outlined in this document including but not limited to depth-damage curves, fragility curves, and disruption to transportation systems. An example of the use of CADDIES 2D for pipe burst scenario is described in section 4 of this document. Moreover, for Barcelona research site, a specific integrated model for the analysis of potential failures of water supply network will be developed and used for the identification of potential flooding affecting critical infrastructures.

[9] http://emps.exeter.ac.uk/engineering/research/cws/resources/caddies-framework/caddies-2d/

### 3.5.2 Direct and indirect damages to Combined Sewer Overflows (CSOs)

The focus enforced by the Water Framework Directive (WFD, 2000/60/EC) is to consider the river basin as a single area of operation, in which hydraulic infrastructures have to be managed in an integrated manner, taking into account the condition of the receiving waters. In this sense, the commitment of the Urban Wastewater Treatment Directive (UWTD, 91/271/EC), the implementation of the WFD as well as the Bathing Waters Directive (BWD, 2006/7/EC) require the managers of urban drainage systems and WWTPs to work in a coordinated manner to reduce the pollution effects on receiving waters, especially in wet weather. Traditionally though, and still nowadays, these infrastructures have been designed and managed separately.

The development of the WFD also implies a higher level of protection for water bodies, enforced to achieve and maintain a good ecological status of water ecosystems. To do so, the WFD sets the need to identify and evaluate the pressures and impacts affecting our aquatic environments. This analysis of pressures and impacts revealed, in the last decade, high levels of mobilized pollutants and high concentrations generated in sanitation systems during wet weather and that directly affect receiving waters.

Combined urban drainage systems are designed to convey wastewater flows to treatment facilities in dry weather and for moderate rainfall events (usually up to 3-5 times the mean wastewater discharges), but as soon as these capacities are exceeded, water is by-passed to receiving bodies (rivers or sea). Wastewater coming from houses as well as industrial sites or collective buildings (like hospitals) exhibit high concentrations of suspended solids, organic loads, nutrients, phosphorus, metals, faecal bacteria, etc. The recent progresses in quantification of micro-pollutants evidenced a high number of traced pollutants like pharmaceutical products, endocrine disruptors, metals, hormones or organic micropollutants. Similarly, the wash-off of natural (unpaved) and impervious areas like roads or roofs produce runoff flows with a high concentration of heavy metals (lead, zinc, etc. accumulated in dry weather), hydrocarbons and coarse debris (Gromaire *et al*. 2001, Chocat *et al*. 2007, Gasperi *et al*. 2008, Becouze *et al*. 2009). During wet weather, different kinds of impacts can be identified:

- Pollution related to urban drainage networks, releasing to receiving waters a mix of storm-water and conventional wastewater (conveying the corresponding pollutants such as: bacteria, pathogens, industrial pollutants, oil and grease, nutrients, organic matter, solids, etc.) Overflows in WWTPs, when the treatment capacity is usually exceeded, so that the quality of the effluent is not as good as in dry weather operation. The effects of discharging highly polluted loads in the surface waters are hazardous (Krejci *et al*. 2005) for biological species, since a sudden decrease of dissolved oxygen affects their life ecological status, on the short term caused by a sudden input of nutrient and phosphorus materials, and on the long term by input of metals, organic micro-pollutants, etc.

- The possible use of waters for recreational activities (e.g. bathing water qualities),but also other activities like fishing, agricultural activities, production of drinking water, etc., may be affected.

Considering these impacts and the still increasing development of urban areas, the management of storm-water flows and the reduction of combined sewer overflows has become a major stake for more and more European cities, from small to medium-sized and big sized cities. Legislation and standards are still mostly based on the number of emissions or overflows in many countries, so that the effects of varying pollutant loads on receiving waters is overlooked. It is clear thus that management of urban wastewater systems, especially during wet weather is nowadays a challenge for managers and operators.

Within the framework of the BINGO project the impacts of CSOs in the case study of Badalona (Spain) are analysed focusing on people safety, reputation and image and, of course, economic damages. Intangible damages will be covered by the two first. A risk assessment for bathers will be carried out according to different CSOs scenarios and based on the percentage of beach which bathing water presents high bacterial contamination according to the BWD thresholds. In order to do this assessment, a previous model will be performed, considering quantity and quality in discharges to the sea, and whereby different scenarios of contamination will be simulated. Some other intangible impacts may occur when citizens lose the trust on the City Council, since the municipality reputation and image might be affected. A study about citizen's view in this regard will be conducted by investigating how they would feel in case of different scenarios of CSOs, and how they felt in previous events. The number of days of non-compliance of the BWD (bathing forbidden and beaches closed) in a representative year or bathing season could be considered as an indicator in this regard. On the other hand, tangible damages will be address too, since CSO might affect different sectors, such as tourism, fishing and leisure, and those affections may be considered as indirect damages. When the BWD contamination thresholds are exceed due to CSOs beaches must be closed, thus, tourists cannot enjoy one of the major touristic attraction and all tourism-related trades (hotels, restaurants, etc.) will be indirectly affected. The same happens with sea activities both of leisure, such as sailing, swimming, windsurfing and scuba diving, and work activities, such as fishing. The chance of adapting the econometric model developed in PEARL project for calculating such damages will be evaluated.

All these indirect impacts will be analysed and a monetary assessment will be conducted. The assessment of future scenarios will allow to compare and define a degree of aggravation in order to propose and implement measures to reduce CSOs and thereby tangible and intangible impacts.

## 3.5.3 Summary of Impact Quantification methods to be applied to Water Cycle in RESCCUE

In the framework of RESCCUE project this methodology for analysing the impacts of CSOs will be applied to the three research sites (Bristol, Barcelona and Lisbon) by adapting the methodology to the particular characteristics of the three cities. For each research site the CSOs will be identified and based on climate change scenarios and coupled 1D/2D flood modelling estimated loadings and resulting outflows (with estimated pollution concentrations) from CSOs will be analysed along with potential mitigation strategies as a means of reducing such loadings. The impacts associated with flows through the CSOs will be quantified as both tangible and intangible impacts (Table 17).

Table 17 - Assessing other impacts within water cycle.

| Impact Type | RESCCUE approach |
|---|---|
| Water Distribution - Disruption | Analysis of regions of likely disruption will be examined whereby receiver to donor relationships are defined to estimate numbers of consumers and critical infrastructures effected as a result of pipe burst scenarios |
| Water Distribution - Flooding | Utilising CADDIES 2D software, multiple simulations of pipe burst effects can be examined and damage/impact estimates determined |
| Tangible indirect impacts on CSOs | Loss estimates as a result of business interruption to different sectors in proximity to or downstream from CSO outflows will be examined and quantified |
| Intangible impacts from CSOs | Effects of increased contamination of environmental sites located within the vicinity of CSOs will be analysed. |

# 4 Quantifying impacts using fuzzy membership functions

Due to the very nature of CI data there may be limitations on the availability of high quality data (either due to costs or security concerns) to carry out detailed analyses. In the absence of such data, obtaining a fuzzy-based perspective on the risks associated with services within a city can be an alternative approach. This approach serves as both to gain an understanding of the impact risks within a study area and also as a means of engaging stakeholders to visualise these potential risks and facilitate a dialogue with respect to the benefits of gaining new detailed data for analysis.

The fuzzy-based approach requires multiple simulations to be carried out whereby numerous assumptions can be assessed and the severity of impacts based on these assumptions are analysed. The fuzzy-based approach is therefore is defined via analysis from two sides that looks at the likelihood of an impact occurring to an infrastructure and the severity of the impact (Figure 43). This information is used to define a Fuzzy Risk Impact score Risk Matrix depicted in Figure 44 that in this instance relates to the likelihood that a grid cell in the digital terrain model would be classified as flooded during a pipe burst event and the impact relates to the maximum depth recorded at that location.

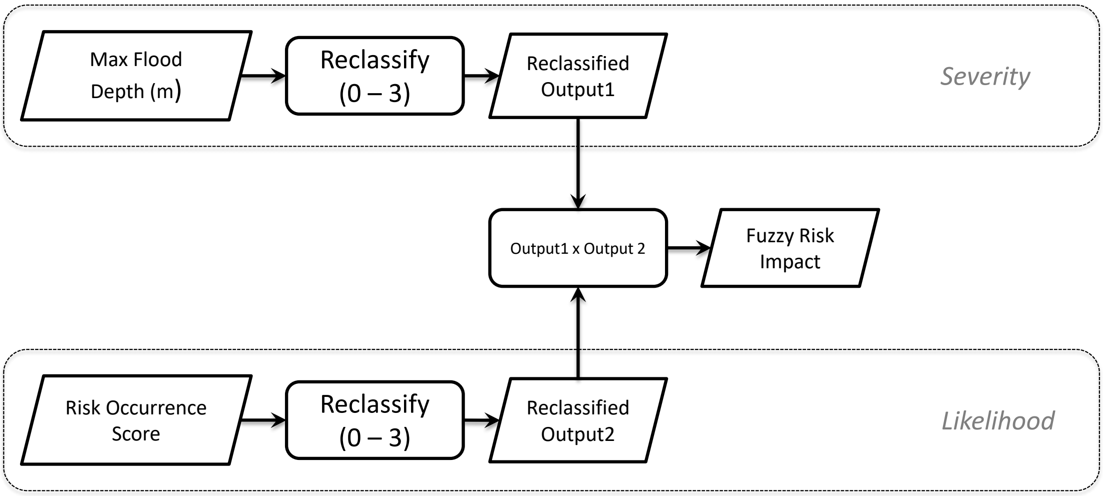



Figure 43 - Deriving Fuzzy Risk Impact scores

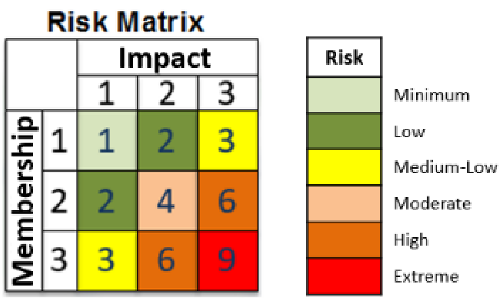



Figure 44 - Simple 3 x 3 Risk Matrix where risk = membership x impact

An example of a fuzzy based approach was shown in related work by Evans *et al*. 2017 for determining the impact a pipe burst scenario could have to emergency services indirectly as a result of power and road network disruption. In this example there were a number of substations distributed around the city of Bristol with some in close proximity to emergency service buildings (Figure 45). Although the spatial location of the substations was known, details as to what substations the buildings were being supplied power from was unknown. The approach used for predicting which substations provide power to which buildings was based on estimating likely “zones of influence” for each substations by generating Voronoi polygons (also known as Thiessen polygons). These are derived via the initial points (substation centroids) being the “seed points” and everything within a zone is closest to that point that is defined by that zone (Weisstein 2017). Figure 46 shows the Voronoi polygons generated based on the electrical substation data within Bristol.

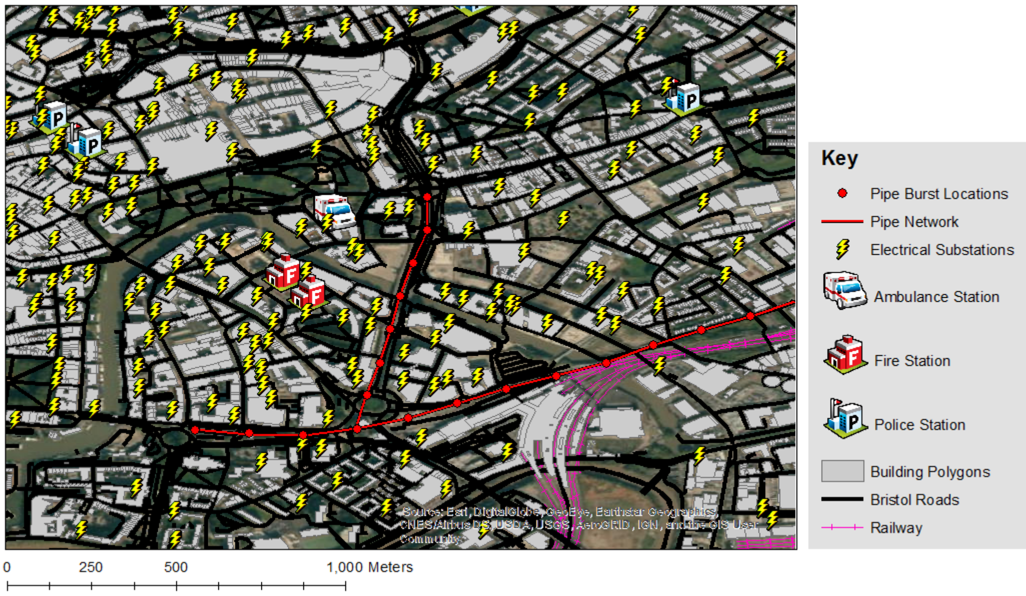



Figure 45 – power substations within Bristol and their location with respect to emergency services (Evans et al. 2017)

A second unknown variable in this study was the water distribution system layout and weaknesses (likely burst locations) in the network therefore the layout of the pipes in was assumed to follow the road layout. For the flood simulation the CADDIES 2D model was used which simulated individual pipe burst scenario at 100m interval spacing's (shown in Figure 45) along the network with an independent flood model was run for each location.


Figure 46 - Voronoi polygons generated via the electrical substation points

An impact analysis was carried out utilising the flood-depth data along with the spatial location of the electrical substation point data revealed which substations are likely to fail (because of being flooded) during specific flood events. This approximation can be used/linked to defined Voronoi zones of influence to estimate areas affected by power loss (from each affected substation). Figure 47 shows this approach where the maximum flood depths generated from a fictitious pipe burst event around the Bristol Temple Meads area. Here based on the impact analysis of the water's interaction with the electrical substations there are two CIs that fall within the impacted zones (Ambulance and Fire Station). Utilising the approach outlined in Figure 43 the associated Fuzzy Impact Risk score in relation to likely powerloss for each of these CI's can be defined. Figure 48 shows that although there is a risk of disruption from a flood based impact (if the pipe were to burst along any of the points depicted in that section of the network) though that level of risk is deemed minimum.

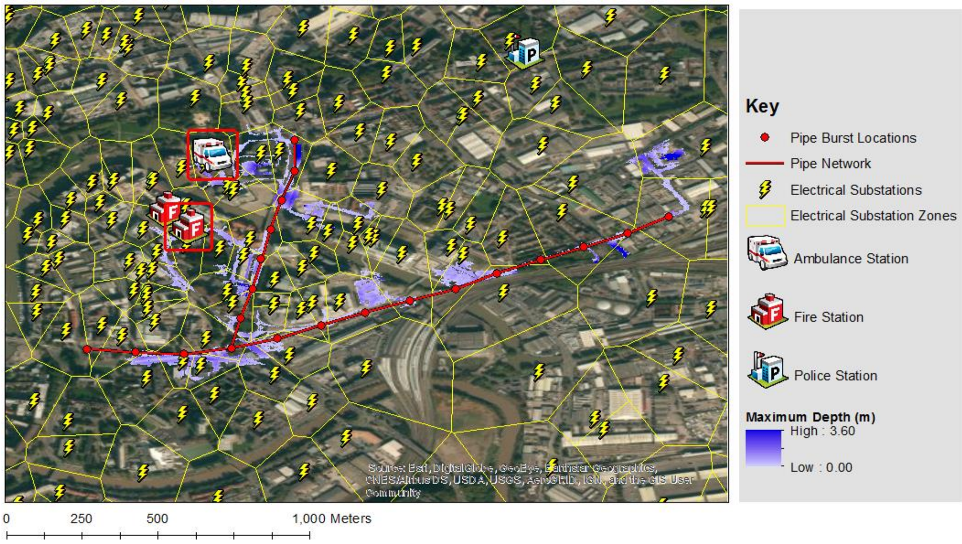



Figure 47 - Potential power disruption based on flooding from pipe burst event


Figure 48 - Indirect risk to emergency services as a result of power loss

As similar more detailed zonal approach for defining indirect impact regions as a result of power loss has been employed within the EU-Circle project when looking at flood impacts on substations and quantifying the associated risks to surrounding properties as a result of such impacts. Figure 49 shows the direct monetary losses to buildings as a result of a flood impact along with the indirect risk of impacts as a result of flooded roads and power outages due to local substation failure. Like that as outline above, this approach again utilises Voronoi zones to define likely service areas for substations and as such the impacts in this regard are defined with respect to risk matrix scores.

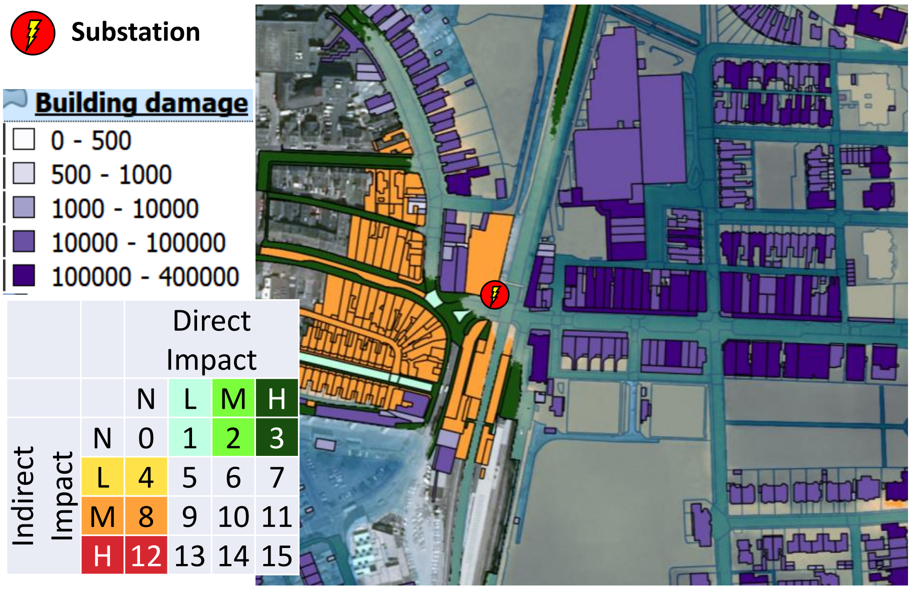



Figure 49 - Direct impacts from flooding and indirect risks of power loss (EU-Circle)

In an idealised approach one would look to use a linked table method whereby interdependencies between substations and properties can be correctly defined. However, due to the sensitivity of this information this may not always be possible and therefore in order to carry out some analyses of the impacts relating to climate events a more “zonal” and “fuzzy” based method can be applied. Although the fuzzy based approach may differ from reality, it still provides a means of establishing likely risks to properties. It is envisioned that this approach would serve as a means of stakeholder engagement to highlight potential risks that could arise due to interdependencies and facilitate in discussion in obtaining data to improve the model to move towards a more probabilistic approach of impact analysis. A summary overview of these fuzzy based approaches is presented in Table 18.

Table 18 - Methods for assessing impacts in study areas where data access is limited

| Input Data Issue | Proposed methodology |
|---|---|
| Lack of spatial information relating to receiver infrastructures from donor providers | In the absence of donor to receiver relationships, methods will be employed to associate fuzzy memberships based upon weighted distance analysis and logical rule based reasoning. Although the resulting outputs may not fully resemble reality it is envisioned that they will help portray a picture of potential risk distributions and impact quantification estimates that can be refined at later stages where more data becomes available |
| Lack of spatial and physical information relating to the severity of hazards. | In the absence of data relating to spatial locations and severity of hazard events. A fast modelling approach can be employed to run small scale models to analyse multiple scenarios and their potential impacts.<br><br>In these instances the ranges of spatial locations will be determined on a logical basis and the severity of the hazards will be derived from looking at similar historical events that have occurred either previously within the city or other areas that are similar in their conditions to the case studies in RESCCUE. |

# 5 Summary overview

The methods outlined in this document have looked at approaches that can be utilised to quantify the level of impacts and risks from given hazards and the extent of their reach. The main methodologies identified for quantifying the impacts to each sector are as follows:

1. **Flood Depth-Damage curves**: Based on reference and/or training data depth-damage curves associated for each considered land use classification can be updated and used to estimate monetary losses that arise as a result of flood based impacts. Improvements to the way the flood depth-damage are being calculated are also being investigated via additional considerations of both porosity of buildings and flood duration
2. **Fragility curves**: Similar in part to that of flood depth-damage curves these graphical functions relate the severity of a given event to the probability or likelihood of infrastructure failure. Unlike that of flood depth-damage curves, fragility curves are applicable and unique to the behavioural response of an infrastructure to a specified hazard including but not limited to: wind, heatwave, cold-wave and snowfall
3. **Performance indices**: When looking at means of quantifying impacts on certain service sectors, these indices can be utilised as means of representing and quantifying the consequences of a service failure.
4. **Traffic disruption**: Similar to that of performance indices impacts on the road network as a result of flooding and snowfall that effect road capacity can be examined in terms of traffic disruption via congestion, loss of working hours and increases in pollution.
5. **Risk to pedestrians and vehicles**: Detailed risk assessments to both vehicles and pedestrians as a result of flood water propagation is being investigated.
6. **Waste service disruption**: Methodologies for assessing impacts of flooding events on the waste sector identified.

7. **Water Cycle impact**: Methods and tools identified for the investigation of pipe burst events and their subsequent impacts in the case study areas identified.
8. **Fuzzy-based impact regions**: Like that of its' direct counterpart, the fuzzy-based approach allows for estimated quantifications of impact regions as a result of an infrastructure failing to provide a service to others.
9. **Indirect damage assessment**: CETAQUA econometric model for indirect damage estimation (including indirect damage produces by CSOs).

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# 7 Annex

## 7.1 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)