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D2.4
MULTI-HAZARDS ASSESSMENT RELATED TO WATER CYCLE EXTREME EVENTS FOR CURRENT SCENARIO (PUBLIC SUMMARY)

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RESCCUE - RESilience to cope with Climate Change in Urban arEas - a multisectorial approach focusing on water

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1. Changes with respect to the DoA
   None. This deliverable, in the format of public summary of D2.2, has been included in the last version of the DoA in order to disseminate the methodology used in the Task 2.2 of the project and part of the achieved results.

2. Dissemination and uptake
   Public summary of the D2.2.

3. Short Summary (<250 words)
   This Deliverable 2.4 is a public summary of the Deliverable 2.2. It presents the different methodologies used in the framework of Task 2.2 of the Work Package 2 (Hazard

assessment for urban services operation) to provide hazard assessment related to extreme weather events in strategic urban sectors. Respect to D2.2, in the D2.4, only main features and general set-up of the sectorial models have been described. Example of results about hazard assessment have also been presented avoiding to show detailed hazard maps, specific relations among urban services in case of cascading effects and geo-references or identifications of critical infrastructures. The methodologies and approaches applied in the 3 RESCCUE sites are quite similar, although the results have been presented separately for each research site. These results represent the baseline scenario in terms of hazard assessment that will be compared with future business as usual and adaptation measures scenarios to be developed within the framework of Task 2.3 of WP2.

4. Evidence of accomplishment
   This report

Summary

Summary Tables

Summary Figures

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1.Introduction

RESCCUE Work Package 2 is focused on the hazard assessment concerning strategic urban services and environment. Task 2.1 was devoted to the identification of potential hazards for strategic urban services produced by a set of selected climate change pressures depending on their significance and the interest of each RESCCUE research site (Figure 1). The work done in this Task was widely described in the Deliverable 2.1 “Identification of potential hazards for urban strategic services produced by extreme events”.

Figure 1: Framework of the Task 2.1.

On the other hand, the aim of Task 2.2 and Task 2.3 is the hazard assessment for current and future scenarios respectively using detailed models and software tools (following named sectorial models although many times integrated model analyzing cascade effects among different sectors have been used). Specifically Task 2.2 treats the development / update, calibration and validation of several sectorial models in the three RESCCUE research sites to be used for the simulation of the effects of specific selected climate drivers on strategic urban services, infrastructures and the environment, while Tasks 2.3 will treat the assessment of the effects of climate change scenarios and the analysis of the efficacy of adaptation measures in terms of hazard reduction.

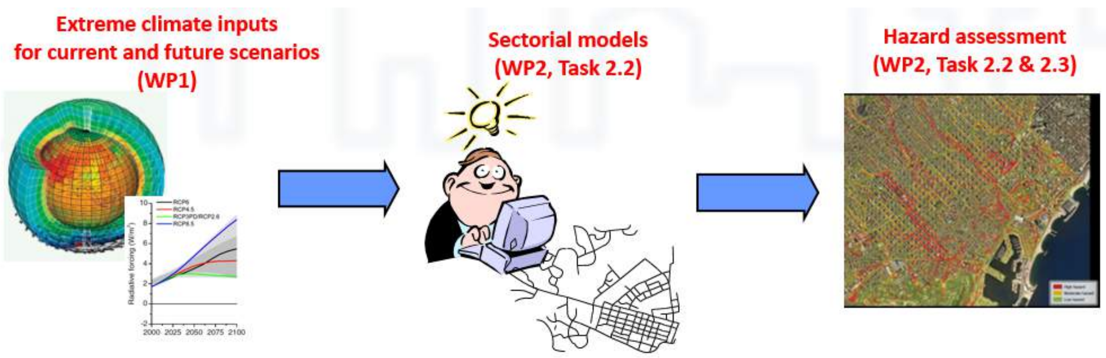

Figure 2: Framework of the Task 2.2 and the Task 2.3.

In this context, one of the main objectives of the Deliverable 2.2 "Multi-hazards assessment related to water cycle extreme events for current scenario" was the explanation of how the use of sectorial models (or the integration of several sectorial models) can help to fully understand the potential hazard related to extreme events and the finally to be used to improve urban resilience though the detailed knowledge of cascade effects.

With this aim, Deliverable 2.2 concerned some initial sections about the building of resilience through sectorial models and their use for the assessment of multi hazards produced by extreme climate phenomena, while, on the other side, for each RESCCUE research site, the selected sectorial models were fully described with specific sections about the set-up/updating (some models will be developed while other ones will be updated on the basis of previous versions), their calibration and validation using field data (measurements and observations) and finally the hazard assessment for the current defined scenario according to specific hazard criteria related to each urban sector.

Due to the strong criticism of the information related to detailed hazard maps and the links among strategic urban services and infrastructures, Deliverable 2.2 has been classified as confidential. Deliverable 2.4, as public summary of D2.2, presents the different methodologies used in the framework of Task 2.2 of the Work Package 2 to provide hazard assessment related to extreme weather events in strategic urban sectors and, respect to D2.2, only general results about hazard assessment are presented avoiding to show detailed hazard maps and the relations among urban services in case of cascading effects. The results are shown separately for each RESCCUE research site.

All the hazard maps produced (present, future and with adaptation measures) for the 3 case studies will be provided as an annex to D2.5.

2. The concept of multi-hazards assessment in the framework of RESCCUE project: building resilience through sectorial models

The main objective of RESCCUE project is to help cities around the world to become more resilient to physical, but also social and economic challenges by generating methodologies and planning measures and strategies to bring this objective to practice and make them applicable to different types of cities, with different climate change pressures.

Specifically, RESCCUE aims to improve urban resilience of our cities through a set of models and software tools that, firstly, assess climate change impacts in several strategic urban sectors like water cycle (water treatment, water supply, urban drainage and waste water treatment), transport, energy supply, and solid waste, and then interconnects them to assess urban resilience for the current state and a wide range of potential future scenarios. Considering the main aim of RESCCUE project, the detailed knowledge of the behavior of our urban systems during extreme climate events represents the initial basic piece of the whole process of the city resilience assessment. The possibility to share information, technical background and learned lessons from past experiences among technicians, utilities and city managers is, definitely, a good starting point to build this knowledge. This kind of information has been used during the task 2.1 for the elaboration of Deliverable 2.1, whose aim was the site characterization and the analysis of each urban service with special focus on their potential link with extreme climate phenomena.

In this context, the use of detailed models and software tools (likely known as sectorial model within the RESCCUE project) is essential to analyze the behavior and the response of strategic services and critical infrastructures with respect to specific pressures and drivers related to climate change, that are the aims of tasks 2.2 and 2.3 respectively. Moreover the outputs of these sectorial models will be used to assess hazard, vulnerability and risk levels related to the above mentioned pressures/drivers for current and future scenarios where a large set of measures and strategies will be simulated and evaluated in terms of impacts reduction.

Once the detailed knowledge of each urban service has been acquired through available data, past experiences and simulation results, then the interdependencies between them and the cascade effects due to failures or extreme climate events can be studied. In the framework of RESCCUE project, this second step is treated by two different approaches characterized by a different level of detail:

1. In the WP2 and WP3 (respectively focused on multi-hazard and multi-risk assessment) the analysis of certain impact events could be achieved via the use of loosely coupled

models and tools (integrated models) (Figure 3). In this case, adaptation strategies and measures will be proposed and prioritized on the basis of hazard and risk reduction but, also, through multi-criteria analysis providing an overview of other kinds of co-benefits (like economic, social and environmental targets) (WP5).

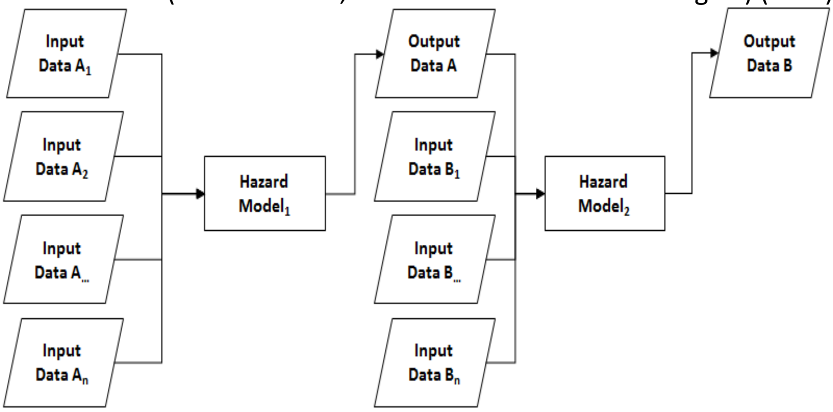

Figure 3: General structure of the use of integrated models for the detailed multi-hazard assessment (source RESCCUE D3.1).

2. In WP4 by using a holistic resilience assessment tool (HAZUR), the relations and the cascade effects among the different urban services can be analyzed in the three RESCCUE research sites during crisis events (Figure 4). In this case, adaptation measures and strategies will be focused on the recovery of the normal functioning of the city and, specifically, of its strategic urban services and infrastructures. This concept will be expressed by the concept of recovery time and the efficiency of the measures and strategies (expressed in terms of decrease of recovery time) (WP4 and WP5).

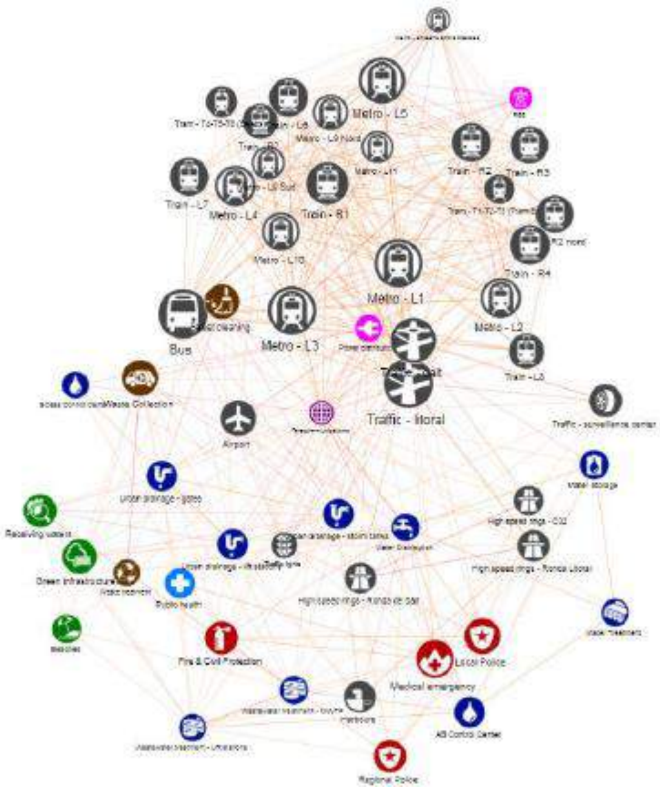

Figure 4: Example of the holistic HAZUR resilience map showing the link among urban services for the case of Barcelona (source RESCCUE D4.1).

It is clear that integration of all the detailed sectorial models and tools representing the whole spectrum of the urban services analyzed in the project in the three RESCCUE cities is not feasible, but this is not the aim of the use detailed integrated model (this approach, with a holistic view and a consequent minor level of detail is covered by HAZUR). The aim of the integration of sectorial models is the detailed analysis of key hazard and risk produced by complex interactions and cascade effects involving specific urban sectors.

So, inputs of hazard/risk models can be used to generate outputs that could be fed into a subsequent hazard/risk model. As an example, the water distribution network is at risk due to seasonal variations of temperature and that these risks are expected to increase as a result of climate change. The impact of temperature on the water distribution network can result in cascading effects on other services. A pipe burst scenario could lead to flooding that can lead to energy grid failure and traffic disruption (Figure 5).

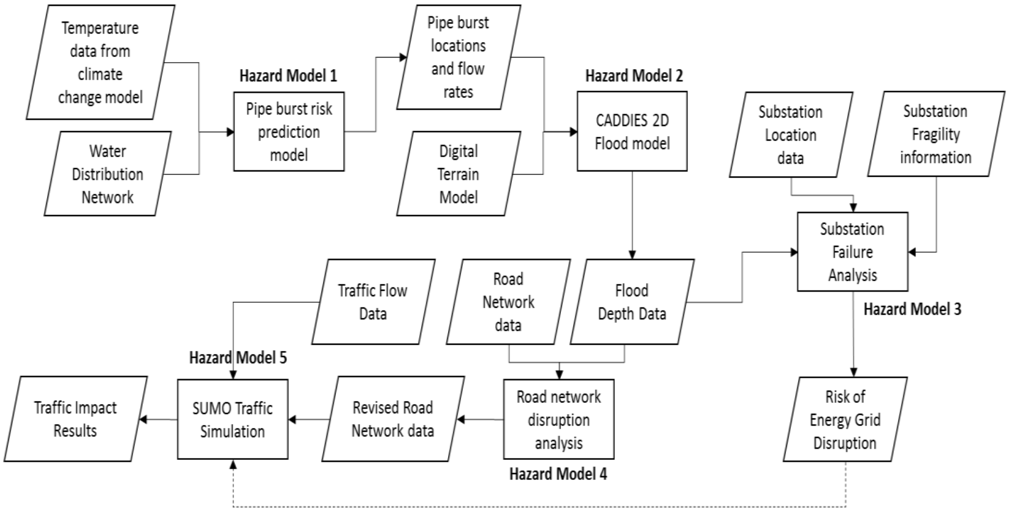

Figure 5: Example of the use of integrated linked models for the multi-hazards and multi-risks assessment (source RESCCUE D4.1).

On the other side, heavy storm events may produce flooding problems with direct and indirect impacts like economic damages, traffic disruption, combined sewer overflows into bathing waters with consequent potential hazards for citizens but, also, indirect impacts in leisure activities, tourism and fishing sector (Figure 6).

An accurate analysis of these impacts requires the implementation and integration of detailed and reliable models and tools (the RESCCUE sectorial models). In this way, it could be possible to carry out an exhaustive multi hazard assessment (Task 2.1 and 2.3 of WP2) and multi-criteria analysis for determining direct and indirect impacts (WP3) produced by extreme events in a context of climate change and to assess all the potential benefits of the adaptation measures to face with it (WP5).

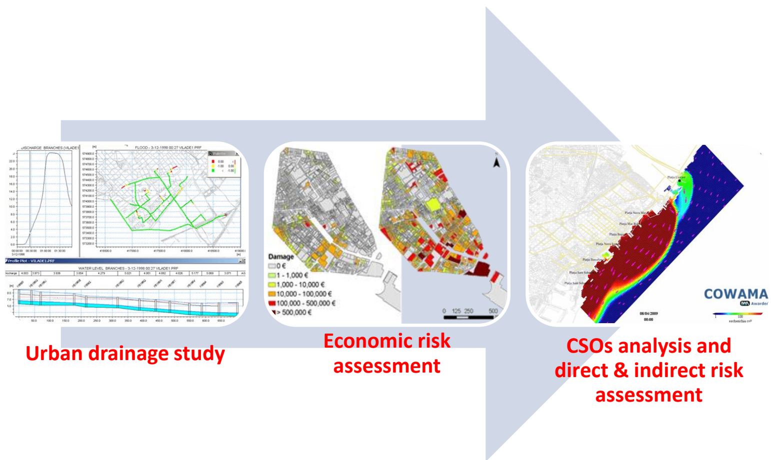

Figure 6: Example of use linked integrated model for multi-hazards assessment (sewer and surface flooding and pollutant loads in bathing waters) in the WP2. This kind of analysis also could provide

relevant information for risk assessment (concerning direct/indirect and tangible/intangible damages) in WP3.

3. Models and data requirements

This section summarizes the models and data required to perform hazard analyses in the RESCCUE case studies. This section also provide information for application to other cities beyond RESCCUE so to understand the exploitation potential/constraints of the proposed solutions.

Within the WP2 of RESCCUE project, a large set of sectorial model have been developed and, in case of field data availability, also calibrated and validated. Floods analysis, treated through urban drainage, tidal and river flooding models, is a common issue of the three research sites, being it one of the main climate hazard for all of them. Several integrated models have been developed on the basis of the outputs of these models in order to analyze the potential cascade effects produced by flooding on other critical urban services like transport, waste, electricity, etc. Water quality and drought models have been also developed for Barcelona research site. Due to the modification of the consortium and the final objectives in Bristol research site, as reported in the second amendment of the project, analysis and modelling tasks concerning drought in this city were replaced with other activities related to stormwater surface separate analysis and simulations.

In the following sections, summarized and general information about sectorial models and several integrations is provided. This information regards modelling set-up, data requirements, calibration and validation and finally general results of hazard assessment.

As summary, the following Tables show the sectorial models developed in the three RESSCUE research sites, specifying the involved urban sectors and their main purposes. The outputs of the sectorial models could be also used for updating the cities resilience assessments developed in WP4 through HAZUR and could be included in the Resilience Action Plans to be developed in WP6.

In Barcelona 8 sectorial/integrated models have been developed or updated, while for Lisbon and Bristol the numbers of developed models have been 4 and 3 respectively (in Bristol the development of an integrated electrical model is currently ongoing due to the new interest shown by the stakeholder Bristol Power and the availability of IREC). This difference is due to the budget distribution in the three research sites and, for the case of Bristol, as said, to the withdrawal of important partners/stakeholders (SASUK and Bristol Water) originally involved in drought analysis of the city.

Table 1: Available RESCCUE sectorial models for Barcelona research site.

Involved sector/s and services	Models in RESCCUE	Main objectives
Urban drainage	1D/2D urban drainage model	Social and economic flood hazard and risk assessment concerning people, goods and properties
Urban drainage and surface transport	Integrated flooding - transport model	Assessment of flood impacts on vehicular traffic
Urban drainage, rivers, coast and power (electricity) supply	Integrated flooding – electrical model	Assessment of flood impacts on power (electricity) supply
Urban drainage and waste	Integrated flooding – waste model	Assessment of flood impacts on waste collection

Beaches	Bathing water quality model	Assessment of the impacts (in terms of people safety and indirect damages) produced by Combined Sewer Overflows (CSOs) in case of moderate and heavy storm events
Beaches, harbor, coastal infrastructures	Sea level rise and coastal area model	Assessment of the coastal flooded areas and infrastructures
Water distribution and urban drainage	Integrated burst pipes - flooding model	Assessment of potential impacts produced by potential failures of main water distribution pipes
Water supply	Drought model	Assessment of water scarcity
Water treatment	Llobregat river water quality model	Assessment of water quality during heavy storm events

Table 2: Available RESCCUE sectorial models for Bristol research site.

Involved sector/s and services	**Models in RESCCUE**	**Main objectives**
Urban drainage	Detailed 1D/2D urban drainage model	Social and economic flood hazard and risk assessment concerning people, goods and properties
Separate surface water model	Integrated flooding - transport model	Assessment of flood impacts due to urban runoff
Urban drainage and surface transport	Integrated flooding - transport model	Assessment of flood impacts on vehicular traffic

Table 3: Available sectorial models for Lisbon research site.

Involved sector/s and services	**Models in RESCCUE**	**Main objectives**

Urban drainage	Detailed 1D/2D urban drainage model	Characterization of flooding hazard
Urban drainage and surface transport	Integrated flooding - transport model	Assessment of flood impacts on vehicular traffic
Urban drainage, rivers, coast and power (electricity) supply	Electrical model (for flooding scenario simulation)	Assessment of hazard impacts on power (electricity) supply
Urban drainage and waste	Integrated flooding – wastes model	Assessment of flooding impacts on waste collection service

The following table provides a summary of the most relevant data required for each model. Overall, these data are generally available for the majority of cities with different levels of approximation. The models can be adjusted based on data availability and stakeholder involvement and inputs are considered fundamental for the modelling process and for a successful assessment.

Table 4: Data requirements of the RESCCUE sectorial models.

Models in RESCCUE	**Main data required**
1D/2D urban drainage model	DTM; GIS data of the drainage network; rainfall observations; water level data; land use map; topography of surface area (at least building polygons to be excluded by 2D mesh).
Fluvial flood and tidal model	DTM, GIS data of the river network and bathymetry; rainfall observations; water level data; land use map; bathymetry of the sea; topography of surface area (at least building polygons to be excluded by 2D mesh).
Integrated flooding - transport model	Flood depth simulation results; GIS data of the road traffic network.
Integrated flooding – electrical model	Flood depth simulation results; GIS location of the power distribution network; observed critical points of the power network.
Integrated flooding – waste model	Flood depth simulation results; GIS location and types of the waste containers and/or collection points; photos and videos of waste container during flooding to validate the model.
Bathing water quality model	Bathymetry, wind and rain data, CSO points, water levels at CSOs, water quality observations in the receiving water body after CSOs.
Sea level rise and coastal area model	

Integrated burst pipes - flooding model	GIS data of the water supply network; critical pipes; water fluxes data or 2D overland flow model and DTM; topography of surface area (at least building polygons to be excluded by 2D mesh).
Drought model	Rainfall data; GIS location of water reservoirs; water level observations in the reservoirs; Evapotranspiration data and land use map.
Llobregat river water quality model	Rainfall data; water level data; turbidity measurements; GIS river network.

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4. Multi-hazard assessment for the Barcelona Research Site

1D/2D Urban Drainage model

Barcelona with a population of 1,621,537 inhabitants within its administrative limits on a land area of 101.4 km^2 (15,980 inhab./Km^2) is located on the Northeast coast of Spain, facing the Mediterranean Sea, on a plateau limited by the mountain range of Collserola, the Llobregat river to the south-west and the Besòs river to the north east. The city benefits from a classic Mediterranean climate and occasionally suffers heavy rainfalls of great intensities and flash floods events. The yearly average rainfall is almost 600 mm, but the maximum intensity in 5 min, corresponding to a return period of 10 years, is 204.7 mm/h and it is not rare that 50 % of the annual precipitation occurs during two or three rainfall events. The morphology of Barcelona presents areas close to the Collserola Mountain with high gradients (with an average of 4%) and other flat areas near to the Mediterranean Sea with lower slopes (with an average of 1%). There are 31 catchments in the city. This morphology produces flash floods in the down city in case of heavy storm events.

The objectives of the coupled detailed 1D/2D drainage model developed within RESCCUE project are:

- Coupled simulations of the 1D sewer flow and the 2D overland flow.
- Provide flooding levels and velocities in the city surface for different return period rain events and different climate change scenarios.
- Provide CSO discharges and pollution for different average weather conditions for different climate change scenarios.
- Provide surface flow parameters to be used as input in the electrical, transport and waste models in order to analyze flooding impacts on these urban sectors.

A summary of the model data is presented in the table below.

Table 5: Summary of the model elements

Model element	Number
Nodes (manholes, inlets, grates, etc.)	66158
Storage nodes (tank bodies)	18
Nodes outfalls	120
Pipes number	67967
Pipes (km)	2164
Pumps	22
Sluices	47
Weirs	489
2D mesh triangles	662071

The model was developed and calibrated using the Integrated Catchment Modelling (ICM) software by Innovyze (http://www.innovyze.com), the sewers data from PECLAB Master Drainage Plan (PICBA'06 , 2006), the Barcelona drainage model developed in the framework of CORFU project (Russo B., 2015), as well as all the data provided by BCASA (RESCCUE partner and public company managing the sewer system of the city) concerning recent executed civil works and field and recorded data acquired by the sensors network (more than 100 limnimeters and 20 rain gauges). A Digital Terrain Model (DTM) downloaded from the "Institut Cartogràfic i Geològic de Catalunya" (http://www.icgc.cat/) with a regular mesh of 2x2 m cell resolution and a precision of 15 cm in terms of ground level and a cadastral map with building information downloaded from the "Sede electronica del Catastro" (https://www.sedecatastro.gob.es/) were also used to generate the 2D mesh excluding the buildings from the 2D domain (Figure 7). In order to connect the 1D sewer models with the 2D city surface model, detailed flow interactions between the two layers (underground 1D and surface 2D) of the model were implemented using experimental relations to characterize the hydraulic efficiency of surface drainage system (Gómez M., 2011) (Russo B., 2013).

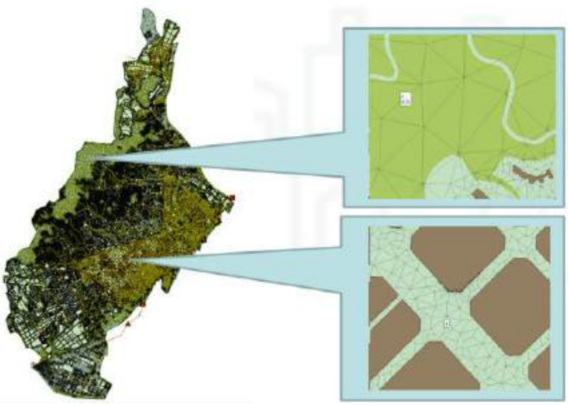

Figure 7: 2D model domain and detail of the different grid sizes

In terms of main results, two types of results are presented and analyzed:

- Sewer capacity for a design storm of 10 years return period. These are the typical results usually obtained in a 1D master drainage plan model focused on the behavior of the network under the design conditions.

- Hazard assessment for pedestrians and vehicles for design storms of 2, 5, 10, 100 and 500 years return period. These results, in terms of flow depths and velocities are very useful because they really show the impact localization in the city surface due to water. These data can also be used for the assessment of flood impact on buildings, critical infrastructures and main urban services. It is important to remark that these types of results can't be obtained with the traditional 1D sewer model, because these only show where the sewer system does not have enough flow capacity but does not show how this water, that cannot be conducted through the sewers, affects the city surface.

The hydraulic functioning of the Barcelona sewer network for a design storm with a return period of 10 years is shown in the Figure 8, where green color indicates free surface flow conditions, yellow color indicates surcharged pipes, orange color indicates piezometric level 0.5 beyond terrain level and red color indicates surface flooding.

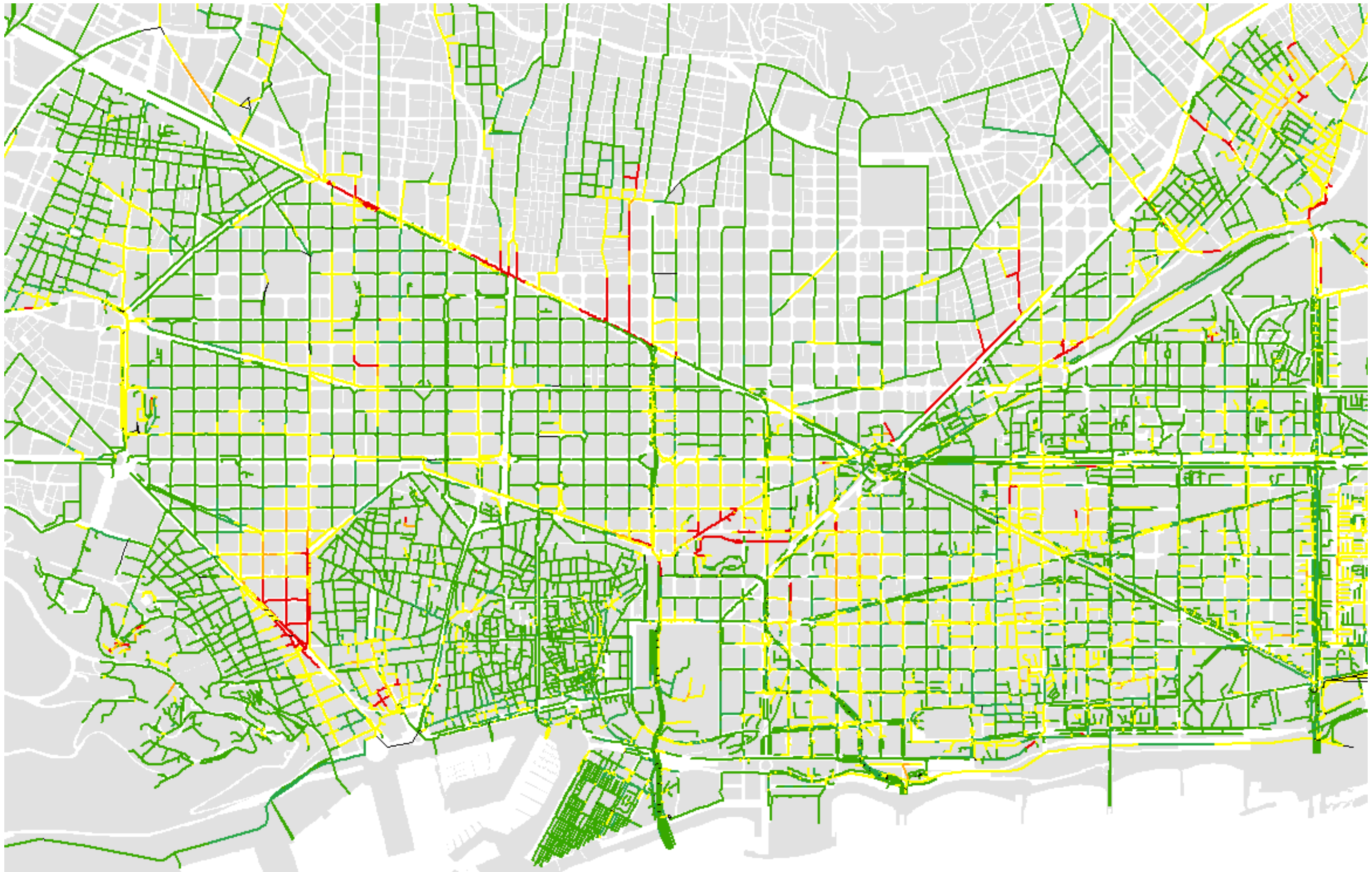

Figure 8: RESCCUE model results for T=10 years.

For the hazard assessment, specific experimental criteria to characterize flood hazard for pedestrian (Martínez E., 2016) and vehicular (Martínez E., 2017) circulation were used.

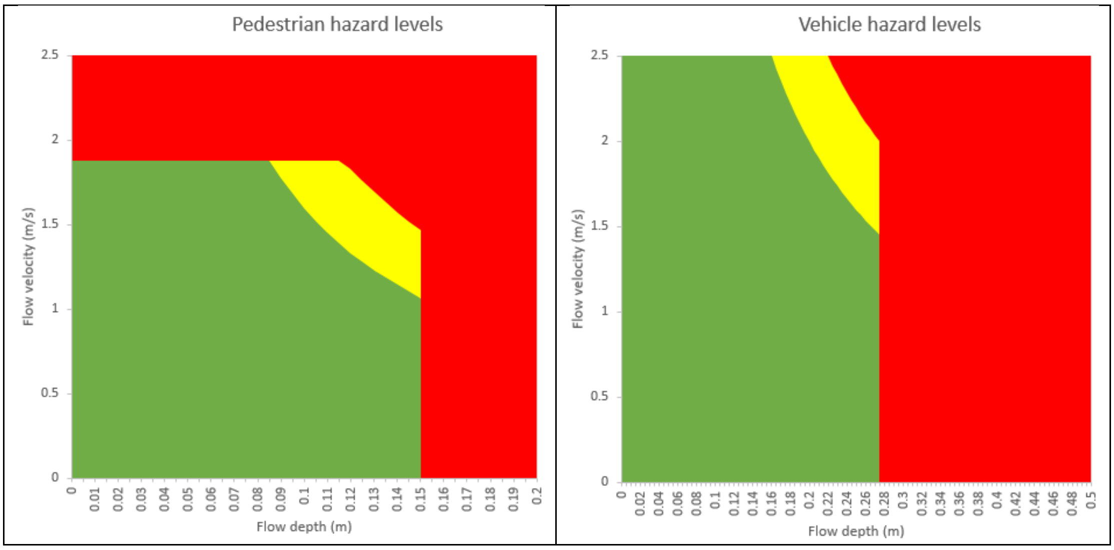

Figure 9: Pedestrian (on the left) and vehicular (on the right) flood hazard levels.

The hazard definitions have been applied to the model results for T=2, 5, 10, 100 and 500 years providing the summary information in Figure 10 and Figure 11.

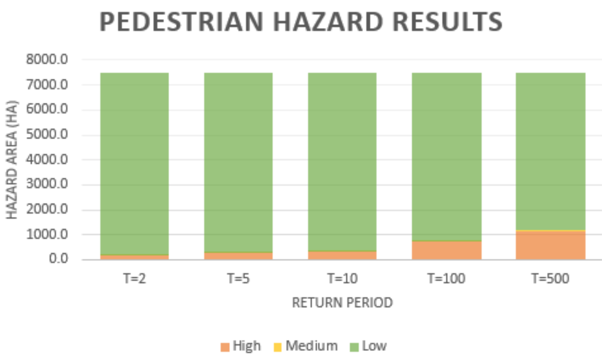

Figure 10: Results for pedestrian hazard levels for different return period rain events.

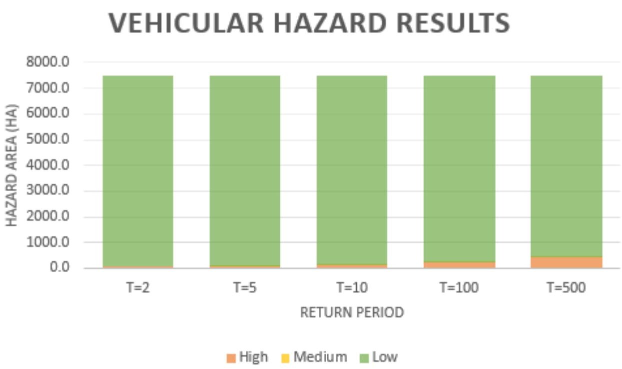

Figure 11: Results for vehicles hazard levels for different return period rain events.

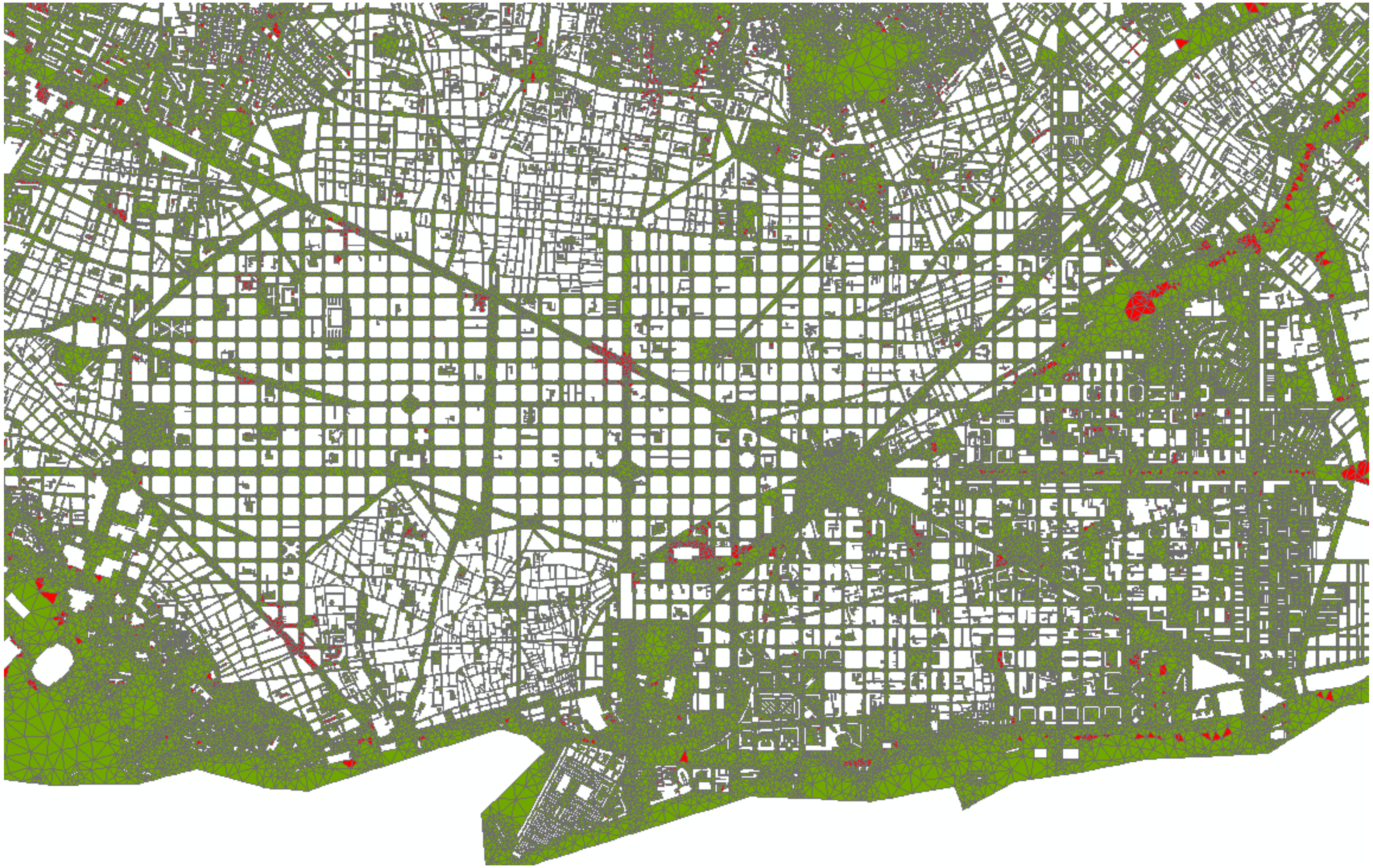

Figure 12: Example of pedestrian hazard results for T=10.

Integrated flooding - transport model

Traffic simulations and modelling in the Barcelona research site has been carried out using a meso-scale model and TransCAD software (https://www.caliper.com/tcovu.htm). The meso-scale traffic model simulates traffic flow at a "link" level whereby a link represents as a subsection section of a road. Each link within a road contains detailed information relating to volume of traffic passing through, types of traffic (e.g. cars, bikes, trucks etc.), travel time across the link, link capacity and a range of other parameters.

As part of the hazard assessment of this work package, flood maps produced for the city of Barcelona were provided and spatially analysed with respect to the road network to derive information as to which roads are effected by flooding within the network. Flood data have been used to determine the hazard inputs for the traffic model, how these inputs are validated along with example inputs derived from real data within the city.

A recent work (Pyatkova K., 2015) looked at reducing permissible travel speeds along link sections in relation to the depths of water present upon those link. The premise here being that if there is standing water on the road above a certain level but below a threshold depth then vehicles can still travel along the road but at reduced speeds, however, if the water is above the threshold value then vehicles would not be able to travel along that section of road.

The data used within the meso-model contains information about the permitted travel speeds along sections of the road network throughout the city. The process of linking flood model outputs to the meso-model therefore would be to use the spatial and depth distribution of the flood data as reference to define (spatially) the location of links that require alteration of their properties of permitted speeds that will be fed within the meso-traffic model (Figure 13).

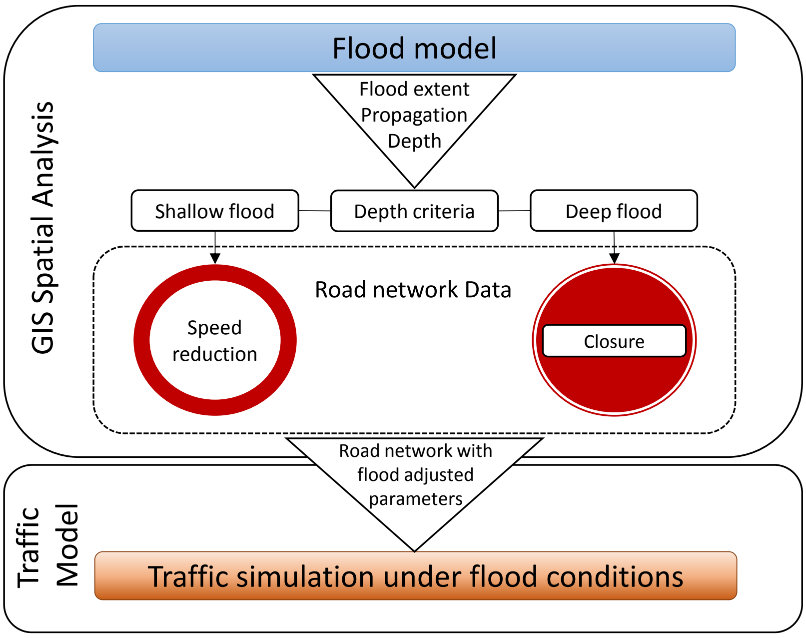

Figure 13: Linking flood model outputs with traffic models.

Within the meso-scale model each link in the road has a set of values assigned to it that relates to the flow of traffic along that link. There are a few properties within the model that relate to the speed of traffic along a given link. The flood model outputs for the city of Barcelona in this hazard analysis have been provided in a Triangular Irregular Network (TIN)/polygon format. The steps required for the GIS analysis component of Figure 13 for producing road network hazard maps are shown in Figure 14. Here 3 types of input are used: Flood Depth data (from 1D/2D urban drainage model), Road Network Data, and Flood Depth rules. By using the reclassification and intersect analyses accordingly Road Link hazard outputs are generated that can serve as inputs into the TransCAD traffic model.

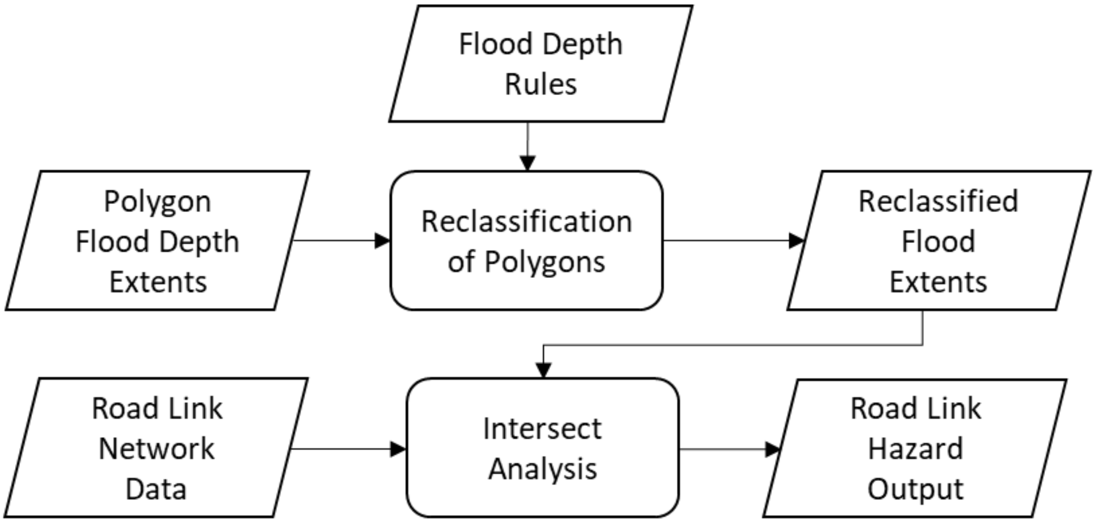

Figure 14: Creating road network hazard maps with polygon based flood data.

The methodology being used of linking flood model data with TransCAD data has not yet been tested (it will be done in the Task 3.4 about impact analysis), thought the theory behind changing the properties of the roads to control traffic speeds is designed within the software. In addition to the parameters that define the status of the road link relative to the surface water depth, a secondary and tertiary factors can also be considered which is the area of flooding and duration of flooding.

For the assessment of flood hazard upon the road infrastructure a GIS base spatial analysis has been carried out (part 1 of Figure 13) and the rules about traffic speed reduction (Table 6) have been applied. Figure 15 shows the effects of a project storm with a return period of 10 years based on maximum recorded flood values. As the severity of the flood event increases, the number of affected roads increases accordingly (highlighted in Figure 16).

Table 6: Parameters for determining effects of flood depths on traffic speed.

Flood Depth Range (cm)	Maximum Permitted Speed kmh^{-1}
0.00 – 10.00	*Roads maximum speed*
10.00 – 30.00	20
30.00 +	0 (*Link closed*)

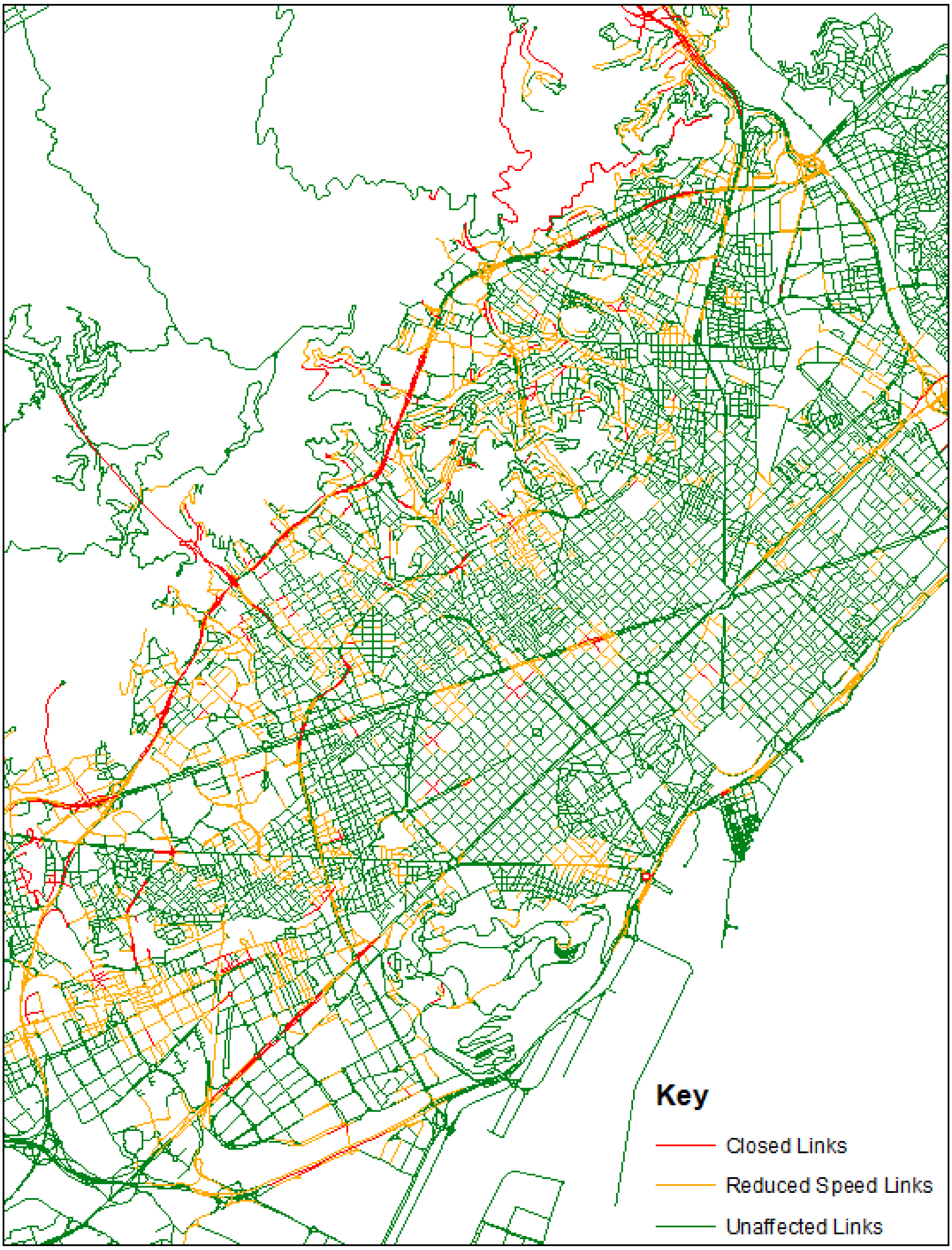

Figure 15: Impact of flooding on roads with T10 event.

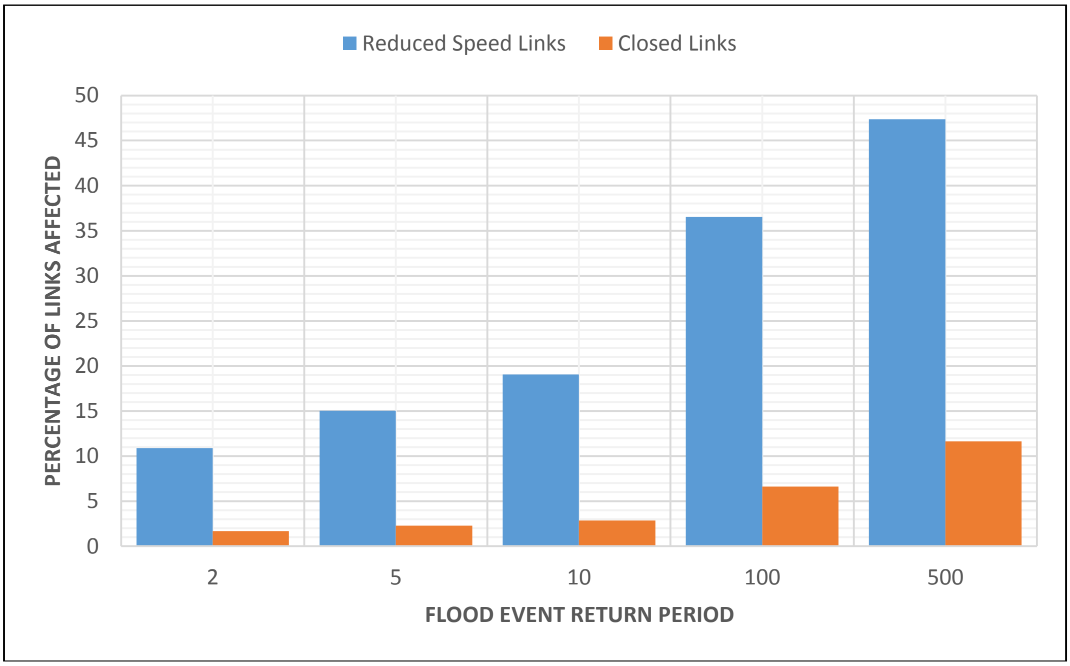

Figure 16: Percentage of road links affected that are located within the flood model domain.

In 2017 Ronda de Dalt experienced some significant flooding that impacted traffic flow and disrupted water supply which affected, these effects impacted Vall d'Hebron hospital (Aiats A., 2018) (Figure 17).

Figure 17: Flooding on the Ronda de Dalt caused disruption in the Vall d'Hebron hospital (Aiats A., 2018).

RESCCUE
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Integrated flooding - electrical model

Currently, the electrical model in Europe and in most cities worldwide is a critical element for the energy sector stakeholders e.g. goverments, regulators, utilities, financial institutions, etc., due to the high dependency of the majority of services on electricity. Global trend in the world is becoming increasingly more electric dependent, as shown by the fact that energy demand is forecasted to grow by 57% between 2006 and 2030 (Vela A., 2016). This, in addition to the fact that the electrical sector faces many threats from a climate change perspective, entails that greater resilience to climate change will be crucial in order to carry out a proper planning and operation of energy demand.

The city of Barcelona has two combined heat power plants (Port and Besòs), which together sum up an installed power of 2,590.8 MW (AMB, 2018). Besides, the city of Barcelona also gathers several lines which interconnect Barcelona to the outskirts in order to meet the customer demand. In Figure 18 a conceptual map of the city of Barcelona at high voltage (HV) level is observed.

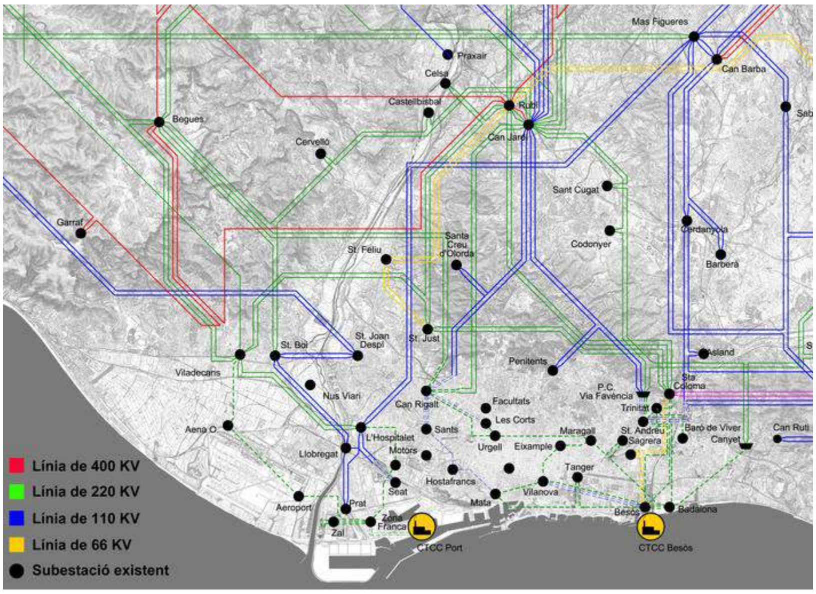


Figure 18: High voltage electrical scheme for Barcelona metropolitan area (AMB, 2018).

Out of the numerous electrical assets in the city of Barcelona, only 50 substations and 1336 distribution centers have been considered regarding the available geographic location data. These distribution centers are located at a distance of 1.5 km inland of the sea and 1.5 km East to Llobregat river and West to Besòs river. As it can be seen in Figure 19, substations are represented with big circles (green is for MV/MV substations and blue is for HV/MV substations) and distribution centers (aggregated loads at MV) are represented with small circles. From a city perspective, analyzing the impacts on medium voltage is sufficient to identify the risks on energy supply. For this reason, it is enough analyzing the impacts on distribution centers, without the need of analyzing lower voltages of the city.

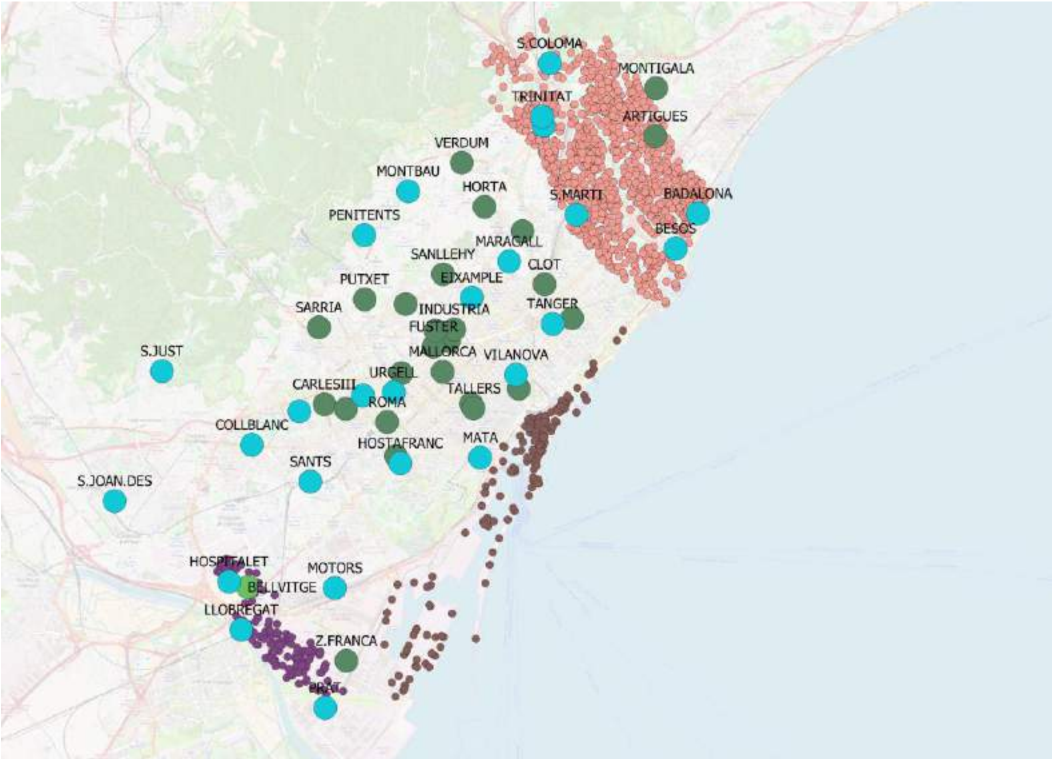


Figure 19: Overview of the Barcelona power system.

To resemble the operation of a distribution system operator, distribution centers have been modelled with lumped loads at MV of 25 kV and 11 kV, without getting down into the LV system. The MV power system has been modelled in a radial structure while the HV power system has a meshed topology as interconnections between substations are highly present in the city.

The flooding impacts are the only analyzed for the city of Barcelona as the heavy storm events are the most threatening hazards for the electrical assets in the city. Various flooding models from different sources at different return periods (T) have been implemented to assess the impact on the Barcelona power system:

- River flooding for T10, T100 and T500 years: study done by the Spanish Ministry of Agriculture, Fisheries, Food and Environment (*Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente*). The output of the studies are potentially flooded zones for water heights above 0 cm due to river flooding.
- Sea flooding for T100 and T500 years: study done by the *Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente*. The outputs of the study show potentially flooded zones for water heights above 0cm due to river flooding. The sea flooding model for T10 is not available.
- Historical flooding produced by heavy storm events: information contained in the Barcelona Drainage Master Plan (PICBA'06 , 2006).
- Pluvial flooding: Hydraulic capacity of the drainage system for T10, T100 and T500 provided by RESCCUE coupled 1D/2D drainage model. The outputs show those flooded zones caused by poor drainage system and producing flow depths.

In the Figure 20, potential flood floods on substations and distribution centers caused by pluvial flooding is shown. Similar maps have been created for the other types of flooding.

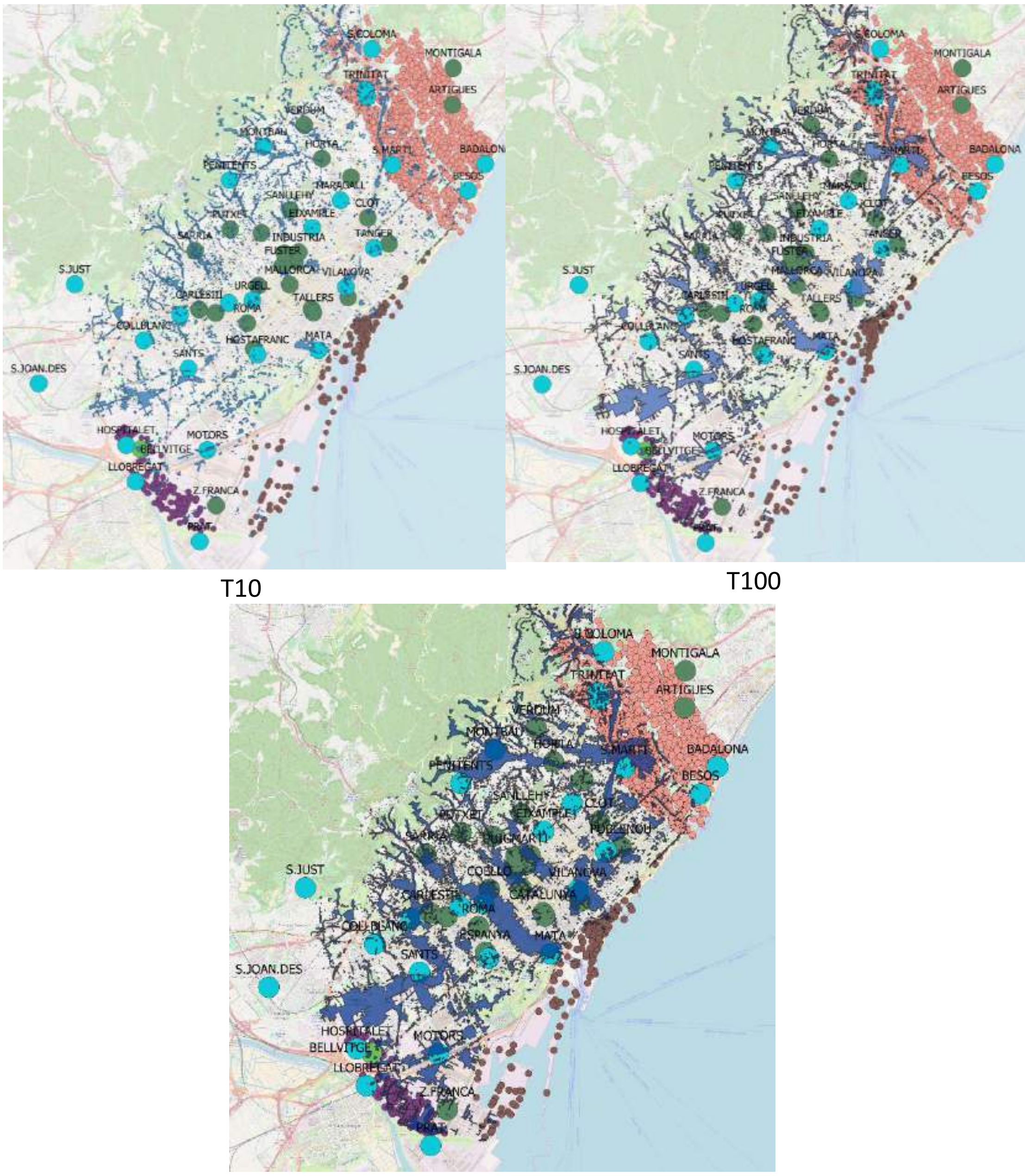


Figure 20: Potential impact on Barcelona power system due to poor drainage system capacity.

Moreover, an impact assessment analysis has been carried out for each of the flooding type to identify the potential number of substations and distribution centers affected. It is important to note that, only 1336 distribution centers close to rivers and the coast are considered for the present study. The following tables show the number of electrical assets flooded.

Table 7: Number of electrical flooded assets in Barcelona due to river flooding.

	Substations		Distribution Centers		
return period	HV/MV	MV/MV	Llobregat area	Coast area	Besòs area
T10	0	0	0	0	2
T100	2	0	1	0	199
T500	3	1	122	0	301

Table 8: Number of electrical flooded assets in Barcelona due to sea flooding.

	Substations		Distribution Centers		
return period	HV/MV	MV/MV	Llobregat area	Coast area	Besòs area
T10	N/A	N/A	N/A	N/A	N/A
T100	0	0	0	14	0
T500	0	0	0	18	0

Table 9: Number of electrical flooded assets in Barcelona due to historical heavy rainfalls.

Substations		Distribution Centers		
HV/MV	MV/MV	Llobregat area	Coast area	Besòs area
1	3	12	2	100

Table 10: Number of electrical flooded assets in Barcelona due to poor drainage system capacity.

	Substations		Distribution Centers		
return period	HV/MV	MV/MV	Llobregat area	Coast area	Besòs area
T10	6	4	2	3	26
T100	6	4	10	3	75
T500	10	7	37	5	117

By observing the previous tables, it is clear that the distribution centers in the Besòs area are the most vulnerable to flooding risks due to river flooding, historical heavy rainfalls and drainage system capacity. Therefore, all electrical consumption being fed from distribution centers within the Besòs area has more probability of suffering a blackout than the rest of areas in the Barcelona city.

Impact assessment of flooding risks within the power system of Barcelona has been carried out through the development of an electrical model using *DIgSILENT PowerFactory*, which is a commercial electrical software for transmission, distribution, generation and industrial plants. As said, for the RESCCUE project, the electrical system of the city of Barcelona has been modelled according to three hazards: river, sea and pluvial flooding. With regard to the detail of the electrical model, the system has been built with two perspectives, that is, a detailed zone where the power system is detailed down to distribution centers, and a simplified zone, where only substations have been modelled. The detailed zones in Barcelona are those directly affected by sea and river flooding, whereas the simplified zones are those prone to historical heavy rainfalls. Such perspective is simply based on the fact that detailed electrical data has been gathered only for those assets located close to the rivers and the coast line.

All 50 substations have been geographically located in the electrical system modelled in *DIgSILENT PowerFactory*, but only 14 have been electrically modelled in detail. Out of the 14 substations, 6 are completely flooded and the other 8 are not flooded but they are feeding numerous distribution centers which are flooded. In parallel, out of the 1336 distribution centers, only 336 have been electrically modelled in *DIgSILENT PowerFactory*. Out of these 336 distribution centers, 328 are directly flooded and the remaining 8 are not flooded but they feed critical loads. The power system modelled allow to observe the cascade effects produced by the flooding of specific electrical assets. As an example, in Figure 21 all the components within the dotted rectangles turn out to be flooded for a specific flood event. Specific maps and detailed analysis have been elaborated in the framework of Task 2.2 for each flood type and several return periods. An example is shown in Figure 22.

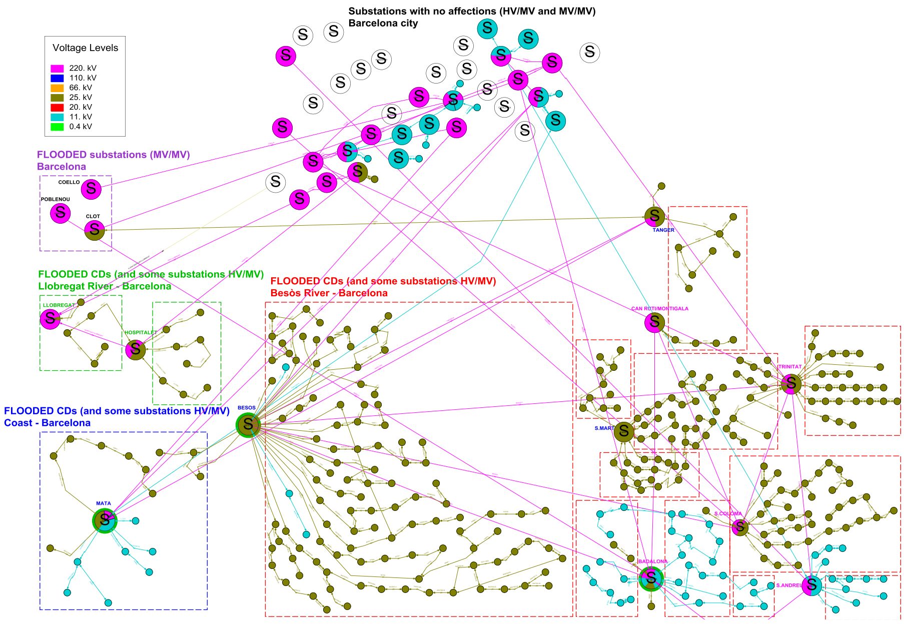


Figure 21: Scheme of the Barcelona power system modelling.

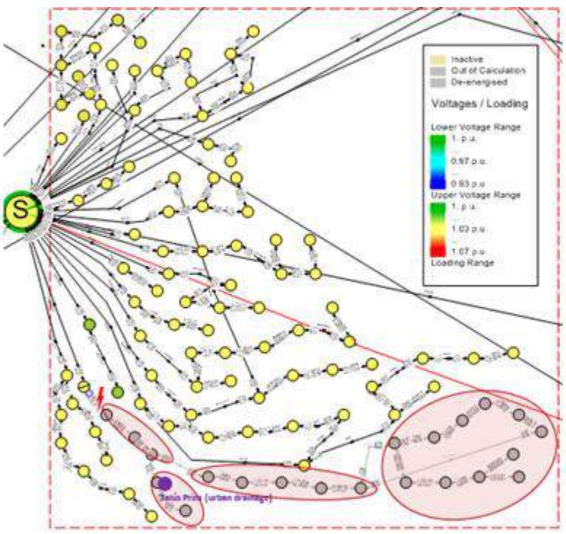


Figure 22: Power flow results after a switch opening in a distribution center due to pluvial flooding (historical rainfall source).

Integrated flooding - waste model

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. 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.

One of the main research effort regarding climate change-related impacts of solid waste sector is focused on offering mitigation measures and strategies in order to reduce the waste greenhouse gases emissions. However, just a few research studies address the reverse problem, how climate change impacts on solid waste sector (Zimmerman R., Faris S., 2010); (Winne S., Horrocks L., Kent N., Miller K., Hoy C. Benzie, M., Power R., 2012); (USAID, 2012); (USAID, 2014); (USAID, 2015).

Landfills are usually the focus when it comes to waste, offering adaptation measures in order to increase the resilience of this sector when impacted by different hazards resulting from climate change (e.g. more frequent urban floods). Nevertheless, before the solid waste be dumped in landfills, the collection process for large Spanish cities starts from a regular collection of household waste municipal service which is carried out through street containers. 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 23). Such type of massive debris carried by floodwaters, as it may be vehicles (Martínez E., 2017), can further constrict a narrow street and increase flooding, thereby creating a closed basin with no outlet for runoff and exacerbating the effects of flooding. When it occurs the likelihood of potential cascading effects due to urban floods increases. This hazard is greatest upstream of culverts, bridges, or other places where debris can collect. On the other hand, inlets and sewers may become clogged with solid waste if it comes out of the container after it loses stability, thereby worsening the drainage system and contributing to exacerbate the flood impacts (i.e. more direct and indirect damages). In consequence, the waste containers stability when exposed to flooding is definitely an environmental, safety, health and economic concern to be addressed.

The main cascading effects due to containers instabilities can be listed as follows:

- *Traffic disruption*: Traffic may be disrupted not just while flood is occurring but also after the event when these containers that were washed away may be laid trafficable locations.
- *Waste collection disruption*: After a flood event, the waste collection may be disrupted if containers were moved from their original location. The municipal

workers have to relocate them and even collect their content in case it came out from the container after losing the stability.

- *Potential sewer blockages*: Potential fractions coming out from the container may block sewers and thereby affecting the drainage effectiveness.
- *Increase likelihood of cascading effects due to flooding*: If containers moved from their original position lay at narrow streets, water depths may increase and therefore the flood consequences will be aggravated. A flood without important consequences may turn into a flood which cause a cascading effect to other sectors.

Figure 23: Real containers instabilities due to flooding in Barcelona.

In Barcelona there are a total of 27,134 containers, which can be classified either according to the fraction they contain (i.e. waste, organic, paper and cardboard, plastic and packaging, and glass), their volume in liters (i.e. 3,200; 3,000; 2,400; 2,200; and 1,800) or the way they are loaded (i.e. lateral, bilateral, rear, underground). The percentage distribution according to their fractions is as follows: 44% (waste), 22% (organic), 12% (paper and cardboard), 11% (plastic and packaging), and 11% (glass). Regarding their loading their distribution is as follows: 62% (lateral), 25% (bilateral), 12% (rear), and 1% (underground). Due to the less percentage of rear and underground loading-type containers when comparing with lateral and bilateral type (Figure 24), only the former have been taken into account in this study, which is an 87% of the total number of containers. Table 11 shows the distribution of studied containers both per districts and type of fraction.

a)

b)

Figure 24: Types of containers in Barcelona: a) lateral load, and b) bilateral load.

Table 11: Total number of containers in Barcelona and studied ones per districts and type of fraction.

District	# of containers	Total # of studied containers	Distribution of studied containers per fraction					% studied
			Waste	Organic	Paper and cardboard	Plastic and packaging	Glass	
Ciutat Vella	1,147	642	152	74	134	130	134	56
Eixample	4,864	4,808	2,213	1,153	477	485	481	99
Sants-Montjuic	2,976	2,369	952	487	313	310	307	80
Les Corts	1,648	1,602	740	218	195	194	192	97
Sarrià-St. Gervasi	3,843	2,528	1,107	472	325	315	309	66
Gràcia	2,135	1,246	394	275	196	188	193	58
Horta-Guinardó	2,463	2,194	730	472	330	332	330	89
Nou Barris	2,144	1,941	661	391	298	294	297	90
St. Andreu	1,986	1,901	713	384	268	268	268	96
St. Martí	3,928	3,928	1,483	831	540	542	532	100

The methodology to assess flood impacts on waste sector in the framework of RESCCUE has concerned the analysis of the stability of the containers that Barcelona City Council has distributed across the city to provide waste collection to citizens when exposed to urban floods. In order to do this, the following three main stages have to be carried out:

1. Coupled 1D/2D hydrodynamic model development
2. Stability functions for waste containers
3. Georeferenced containers location

The details of the 1D/2D coupled model development has been provided in the first section of this document. Concerning the stability functions for waste collections, these functions have been developed based on an analysis of forces acting on a flooded container by establishing equilibrium conditions for the different modes of instability (i.e. sliding, toppling and floating) (Figure 25). These functions are dependent on both hydraulic variables, velocity and water depth. Moreover, the characteristics of each container (e.g. volume, dimensions or fraction they may contain) will determine the shape of each function. The obtained stability thresholds have been employed to analyze the potential behavior of containers against floods in Barcelona caused by historical (model validation) and low-return-period design storms (i.e. 2, 5 and 10 years).

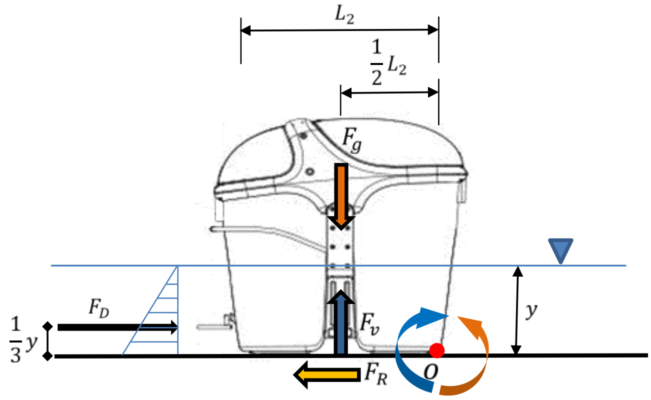


Figure 25: Forces acting on a flooded container (Flow direction parallel to L2).

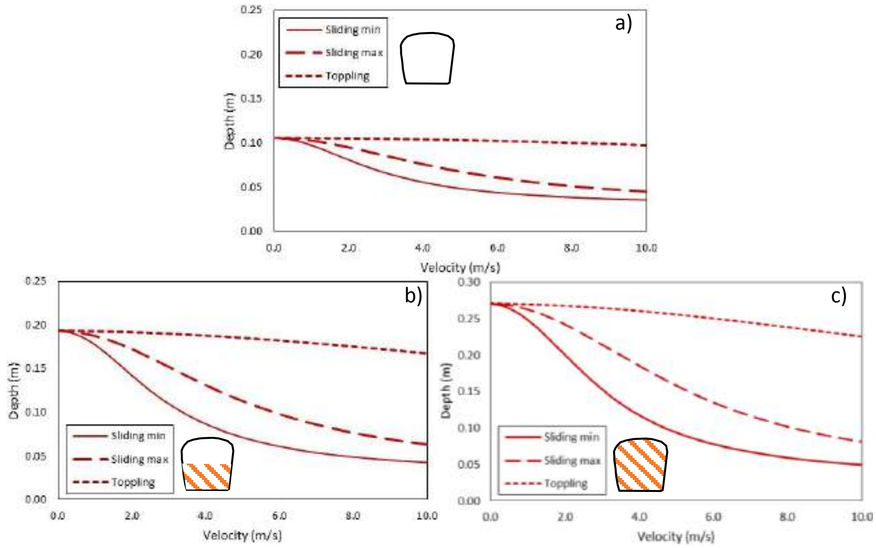
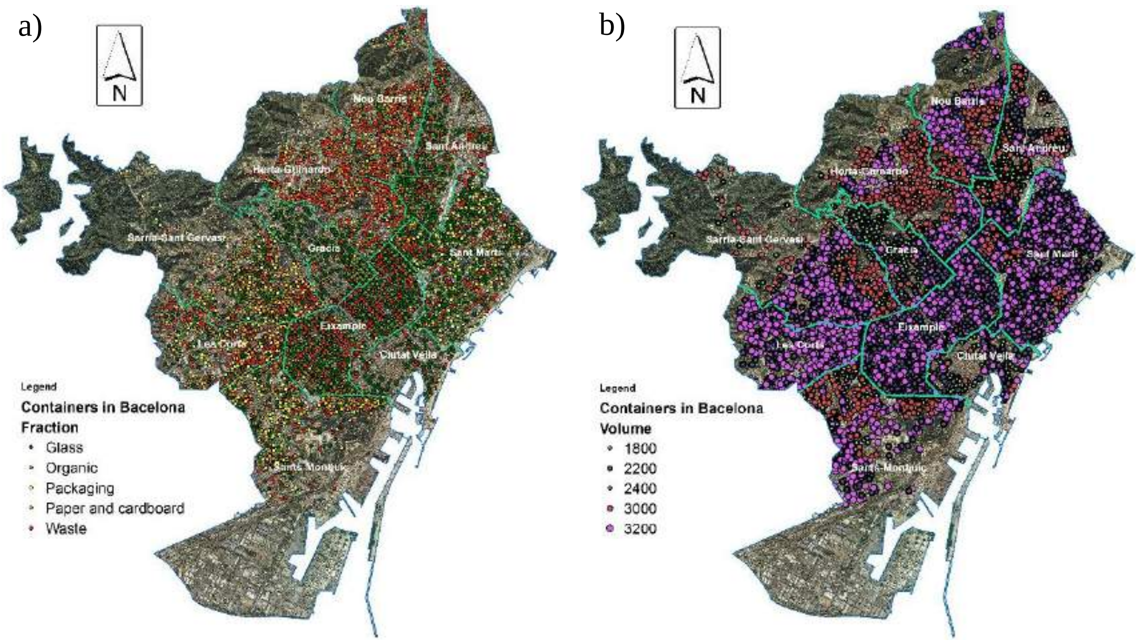


Figure 26: Sliding and toppling stability thresholds for a lateral and 3,200 l container, L2 flow direction, waste fraction and a) empty container scenario, b) 50% filled container scenario, and c) full container scenario.

On the other hand, Barcelona City Council performed a GIS-based map with the location of all types of containers across Barcelona City (Figure 27). This information has been essential in order to study if their current location may lead to a potential instability. Therefore, the resulting outputs from the hydrodynamic model (i.e. velocities and water depth within the studied domain) will be related to the containers and by applying the derived stability functions, those containers potentially unstable will be identified.



Note: due to the great amount of containers, in some cases a dot indicates a location for a set of even five containers of different fractions/volumes. Therefore, within the map only a type of container, either classified by volume or fraction, is represented for each dot.

Figure 27: Containers distribution in Barcelona classified according to a) Fraction type, and b) Volume.

The integrated flooding-waste model was validated using the data of an historical flooding event occurred in Barcelona on 30th of July 2011. The cumulative rainfall was 30.4 mm, while the maximum rainfall intensity in 20 minutes was 105.9 mm/h (corresponding to a return period of 8 years approximately). For this event, the outputs of the Barcelona urban drainage 1D/2D model (i.e. water depths and velocities in each grid cell) were employed to study the potentially unstable containers within the flooded area. A recorded video of the 30th of July 2011 flood, for a specific critical spot of Ciutat Vella district is available and was used to provide a validation of the reliability of this study and, namely of the adequacy of the proposed stability thresholds the integrated flooding-waste model.

Note: Only the empty containers scenario offers instabilities.

Figure 28: Validation of the present containers stability study based on a recorded video of the 30th of July 2011 flood in Ciutat Vella district.

Design storms of 2, 5 and 10 years return period have been performed to be employed as inputs for the Barcelona hydrodynamic 1D/2D coupled model developed within RESCCUE project. Therefore, only quite common rainfalls have been considered, thereby assessing a very a frequent issue unlike the traditional assessments for heavy rainfalls. In Figure 29 maps with the potentially unstable containers are shown, for the three considered scenarios (i.e. empty, half-full, and completely full) and return periods of 10 years. Moreover, the number and percentage of potentially unstable containers for each district was also calculated. The analysis has indicated how vulnerable a district is regarding containers instability, being Les Corts, Sarrià-St Gervasi, Gràcia and Horta Guinardó, those most vulnerable.

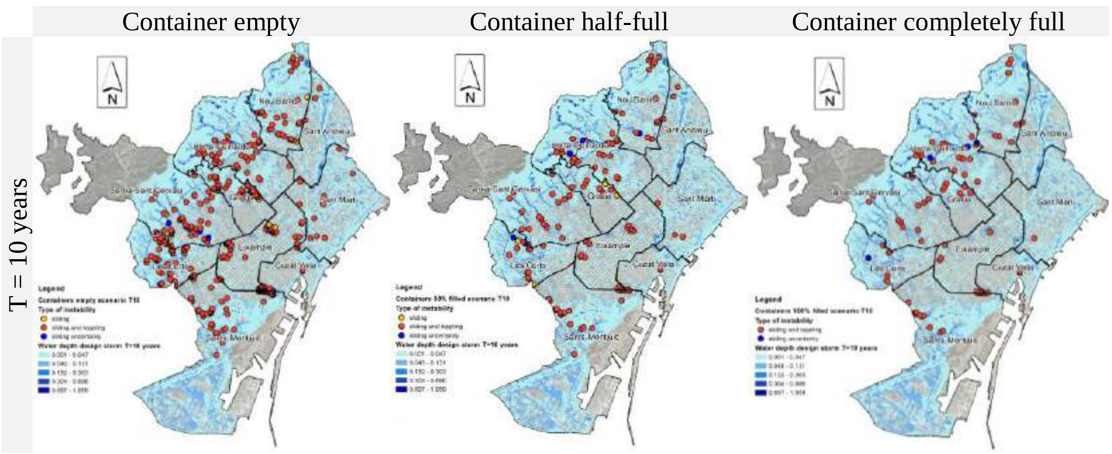


Figure 29: Potentially unstable containers in Barcelona for the three considered scenarios (containers empty, 50% filled and full) according to 2, 5 and 10 years return period design storms.

Bathing water quality model

The sea water model developed within RESCCUE project aims at assessing the impacts of Combined Sewer Overflows (CSOs) on the bathing water quality of the beaches in front of Barcelona. The impacts of CSOs on the water quality are evaluated in terms of simulated E. Coli concentrations in the sea water since this is one of the two mandatory parameters of the bathing water directive (2006/7/CE), the other one is IE (Intestinal Enterococci) but not so much historic data on this parameter were available for this study. So, the marine model has been used to simulate the spatial and temporal distribution of sea water E. Coli during and after CSO events. E. Coli concentration measurements (from local water authorities and municipality) were used to validate the model. The model is then used to simulate hazard maps for people bathing in the sea. The sea water quality model focuses on bathing water quality of the Mediterranean beaches, therefore the effects of CSOs on Besòs and Llobregat river are not simulated.

Every summer several (usually less than 10) CSOs events occur in Barcelona and the sea water quality might not comply with bathing water quality standards up to few days after a CSO event. Poor water quality affects people bathing and swimming in the sea and tourist, sport and leisure activities close to the beaches. Barcelona has approximately 5 km of sandy beaches facing the Mediterranean Sea. During rainfall events (usually larger than few mm) CSOs occur through the approximately 5 CSO structures located along the beaches of Barcelona. Figure 30 shows an example of a sea water quality simulation after a CSO event.

Figure 30: Sea water quality simulation after a CSO event in Barcelona (Red=high; Blue=low E.Coli concentrations in sea water).

The sea water quality model was developed using the software MOHID Studio from Bentley Systems. The model aims at simulating near shore (within few hundred meters from the shore line) sea water Escherichia Coli concentrations after CSO events. The model was originally developed within the COWAMA (Coastal Water Management) project (Sunyer D., Malgrat P., Gutiérrez E., Clochard B., 2007) (Sunyer D., Malgrat P., Leitão P., Clochard B., 2008) that provided a computational model operating since 2007 for real time simulations of bathing water quality of the Barcelona beaches. The new marine model used in RESCCUE includes a new computational 3D grid obtained from new bathymetry measurements made in 2016 and a calibration and validation with new E.Coli measurments from 2014-2107.

The sea water quality model simulates both the hydrodynamics of the sea in the coastal region and the contaminant transport resulting from CSOs. 3 nested model domains are used to simulate hydrodynamic processes from the large regional scale to the local near shore scale of Barcelona. The marine model inputs are:

- Time series of CSOs water discharge for every CSO structure in Barcelona obtained from the 1D/2D (sewer network / surface stormwater runoff) urban drainage model by simulating rainfall events using observations from local pluviometers
- Rainfall time series from 4 different pluviometers in Barcelona applied to the model based on Thyssen polygons
- Wind speed and direction taken from national scale circulation models (information provided by Puertos del Estado)
- Air and water temperature and solar radiation based on local station measurements
- Main E. Coli input concentration from CSO water discharges (fixed to 10^6 cfu/100ml on the basis of field measurements).

Water quality data (bacterial concentrations), essential in order to calibrate and validate the model, were collected by local authorities at 10 different beaches of Barcelona. Three different periods with available sea water quality data after CSO events were simulated in order to calibrate and validate the model. The calibrated model parameters were the wind drag coefficient and the E. Coli mortality rate. Figure 31 shows the comparison of the simulated E. Coli concentrations with the observed concentrations at approximately 10 different locations along the beaches of Barcelona. Overall, the model can reproduce both the order of magnitude and the patterns of the observed E. Coli concentrations.

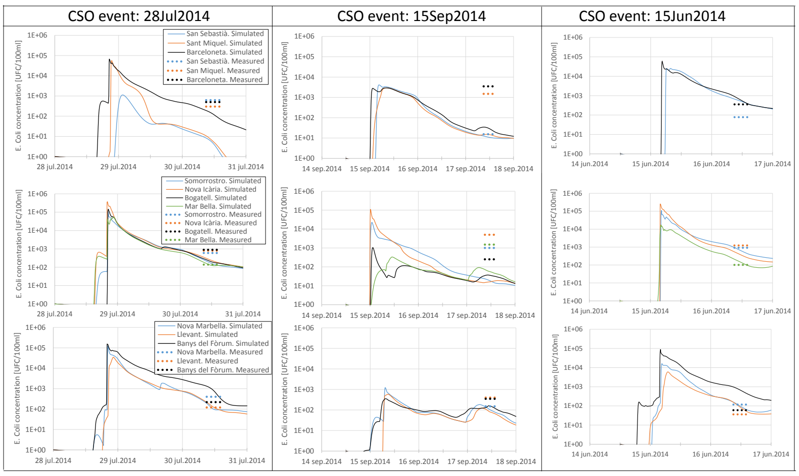


Figure 31: Simulated E. Coli concentration vs observations during 3 different CSO events at different beaches of Barcelona.

This model was finally used to elaborate hazard maps for people bathing in the sea of Barcelona. The hazard maps were obtained by applying the hazard criteria shown in Table 12. The threshold values shown in the table are similar to the municipality definitions of insufficient, good and excellent water quality (EC, 2006). The concentration of E. Coli were simulated before and for the few days following a CSO event and the hazard maps significantly change as a function of time (i.e. high hazard occur immediately after the CSO event, whereas low hazard is likely to be re-established within 24-48 hours after the CSO event).

Table 12: Hazard levels for bathers used in the hazard assessment for Barcelona research site.

Hazard criteria	E.Coli concentration [ufc/ 100 ml]
Low	<250
Medium	250<x<500
High	>500

Figure 32 shows the observed rainfall event used to simulate the hazard maps. The figure shows that there are 2 different rainfall events: the first and large rainfall fell on the 28th of July 2014 and a second minor rainfall on the 29th. Figure 33 shows the hazard maps for people swimming in the sea water of Barcelona. The results show that the hazard significantly changes as a function of space but also of time during and after CSOs. The hazard is high and close to the coastline during the CSO event (28 July at 20:00); subsequently, the high hazard area expands and becomes lager. Low hazard is re-established, after approximately 1.5-2 days (30 July at 12:00) after the first CSO event. The time needed to re-estabilish the low hazard is extended due to the occurrence of a second CSO event caused by the small rainfall of the 29th of July.

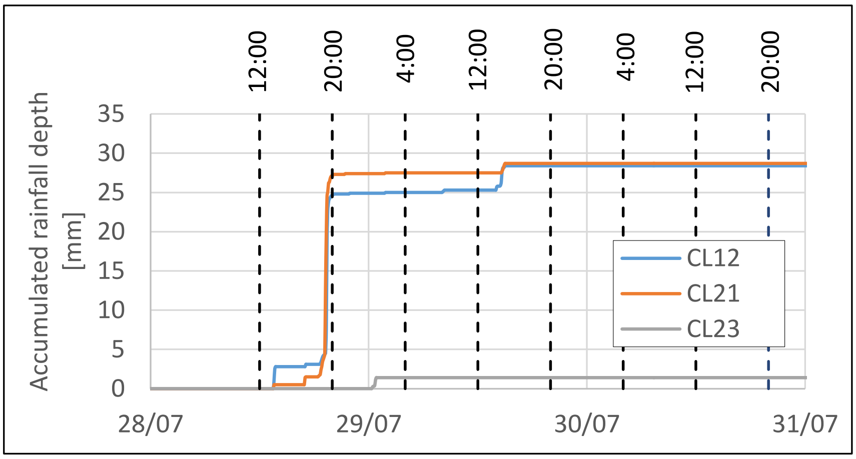


Figure 32: Rainfall event used to simulate hazard maps after CSOs. The vertical dashed black lines show the timing at which the hazard maps are extracted.

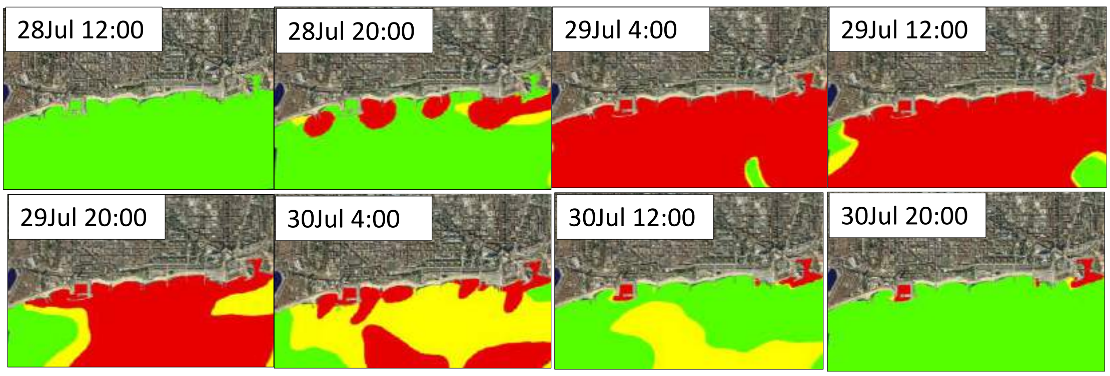


Figure 33: Bathers hazard maps at different times before, during and after a CSO event.

Integrated burst pipes - flooding model

Underground water supply network is designed to withstand the variability of forces during its lifetime before failure occurs. One of the leading causes of failure of the water distribution system is due to pipe burst. Several studies were conducted analysing the influence of local weather conditions on pipe failure with increased pipe failure being observed in winter and summer periods, mainly during periods of freezing and drought. The effects of a burst water pipe can be quite severe resulting in significant visible damage due to the subsequent flooding, cause disruption to services such as transport and energy distribution, or less visible but severe damage over time via underground erosion leading to development of sinkholes. Disruption of the water supply network is not only a flood risk problem, because its failures can result in loss of water to residential, commercial and industrial regions (Evans B., 2018).

As described in the Deliverable 3.3, a very representative event occurred on the 24th November 2016, in Barcelona where there was a series of cascading effects produced by a main pipe burst generated by an unknown failure. Specifically, the pipe burst determined serious traffic disruption in high speed rings (6 hours of queuing) and a water supply cut during 3 hours approximately affecting one of the main hospital of the city (Vall d'Hebron) and 10000 inhabitants. During 2 hours emergency room of the hospital did not work and 33 hospitalized patients were affected.

Figure 34: Pipe burst failure in Vall d'Hebron occurred on 24th November 2016 causing local flooding and other important indirect impacts.

Within RESCCUE framework, an integrated sectorial model has been developed in order to identify critical assets affected by potential failures of distribution pipes. The unavailability of critical (more susceptible to failure) points of the water supply network obliged to enlarge the scope of the analysis of potential failures to the whole city network.

The final objective of this analysis was the detailed modelling of the potential failures affecting significant areas and key infrastructures of the city. Specifically the use of information concerning digital surface model, water supply network (including location, pipe size, circulating flow and time for potential breakage repair) and sag points provided the identification of critical assets (pipes, pumping station, etc.) according to the potential consequences of its failure. One of this point was selected and the local flooding effect produced by this specific pipe burst was simulated using the 2D overland flow module of the coupled 1D/2D model developed for the analysis of urban drainage service.

The most critical point of the water supply network was identified according to the potential consequences of its failure. This point corresponds on an underground main pipe in Roger de Flor Street and the potential failure was located at the crossroad with Ausias Marc Street. The potential failure of this pipe could generate significant impacts and cascade effects in the nearness of Barcelona North Station. This point is a historic flooded area of the city. Moreover, according to the information provided by Aigües de Barcelona, this pipes suffered a recent failure in 2010 causing local flooding. In order to assess in detail the potential flood hazard and impact produced by this failures, a 2D overland flow simulation was carried out using the 1D/2D urban drainage model developed within RESCCUE. According to the information provided by Aigües de Barcelona, the failure was simulated through a hydrograph with an instantaneous peak flow of 700 l/s and a base time of 3 hours. The results of this analysis are summarized in the following hazard map (Figure 35), where flow depths and the location of critical infrastructures and services are shown. Particularly, for this local flooding, some subways and train stations could be affected, such as a power distribution center a local police station and a local health care center.

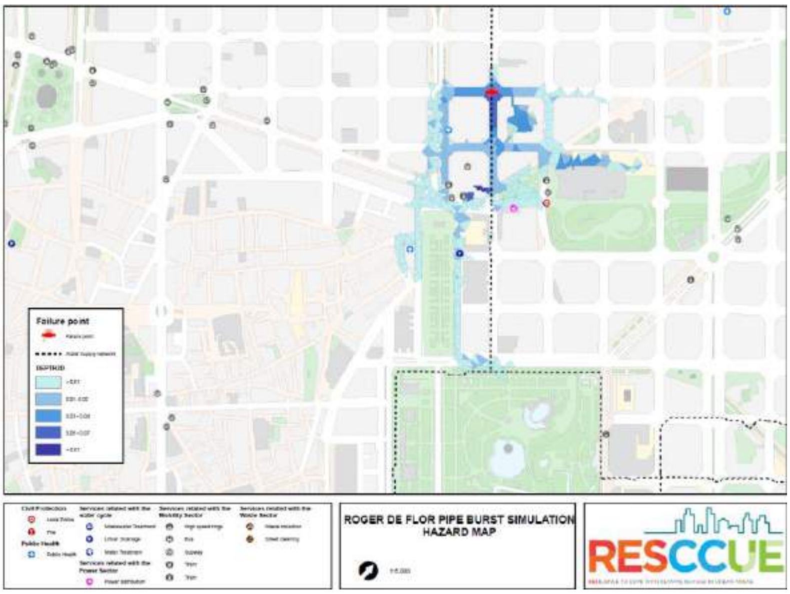


Figure 35: Hazard map concerning Roger de Flor pipe burst simulation.

Due to the lack of the information related to critical points of water supply network (in terms of points with more susceptible to failure), the final aim of the analysis described in this chapter was not the elaboration of hazard maps regarding most probable and critical burst pipes, instead it was to propose a consistent method to analyze potential impacts of burst pipes using 2D overland flow model and key information about location and types of critical infrastructures of strategic urban services. In a real implementation, the selection of critical pipes that could be broken should be more related to pipe characteristics and location (age, material, traffic load, previous problems, etc.). This kind of information can be used by tools like Hazur in order to analyze in depth cascade effects produced by potential burst pipes failures.

Drought model

Water supply in Barcelona is ensured by the water resources of the Llobregat's and Ter's basins. Both watersheds have their upper part regulated by reservoirs which enable to modulate the water resources needed. Barcelona's city is located far away from these reservoirs but the drought state directly depends on the stored water volumes. When these volumes are lower than some specific levels established by the Drought Plan developed by the Catalan Water Agency ACA (Agència Catalana de l'Aigua) *(PES – Pla especial d'actuació en situació d'alerta i eventual sequera)* the city may enter in different drought states, each of which entail several restrictions (leisure activities, irrigation, industrial uses, etc.).

The purpose of this resource and drought model is to reproduce the water contributions that arrives to the reservoirs at a monthly time scale depending on the precipitation fallen over the sub-basins of each dam. In the Llobregat's basin there are found three dams regulating the flow of the main rivers. At the catchment of the Llobregat's river it is found la *Baells* (109.5 hm^3) which represents the 52% of the total water reserves of this basin. The other reservoirs are located upstream of the Cardener's river. First, la *Llosa del Cavall* (79.4 hm^3) and approximately 10 km downstream *Sant Ponç* (24.4 hm^3) which represent the 37% and the 11% of the total reserves respectively. On the other hand, at the Ter's basin, there are found the Sau's reservoir (151.3 hm^3) and the Susqueda's reservoir (233 hm^3) both intercepting the water of the Ter's river. The first one represents the 40% of the total reserves whereas the second one the 60%. According to the Management plan for the river basin district of Catalonia (Pla de Gestió del districte de conca fluvial de Catalunya 2009-2015) developed by ACA the entity responsible for the water resources in Catalonia, the city of Barcelona is served by the water of the Llobregat (38%) and Ter's river (55%), the remaining 8% depends on other underground resources. The regulation of the rivers upstream the basins in the reservoirs enables to modulate the river flow to cope with the demand of the city.

Finally, it is also mentioned that both systems Ter-Llobregat work together in parallel. This means that the drought state comes determined by the total stored reserves in both basins. Only when the system is unbalanced (one of the systems is notably scarce in terms of water reserves in comparison with the other) the drought may come determined by one of the systems, but looking to the historical time period this situation is not very common.

The Task 2.2 only concerned the development of the models (SIMGES and HBV) and not (yet) their applications to evaluate current drought period, problems in water balance, future and mitigation measures scenarios (effects of non-conventional water resources) etc.. These issues will be tackled in future task 2.3.

Simulations of the volume contributions at each reservoir have been carried out using a HBV model. The HBV is an integrated hydrological modelling system developed at the Swedish Meteorological Hydrological Institute. The model is based on three different reservoir modules: one simulates the soil behaviour, the second one the upper reservoir and finally the lower reservoir that accounts for the groundwater base flow. The model requires physical properties of the basin as well as the climatic inputs, including precipitation, temperature and potential evapotranspiration. The time scale for the input data is daily.

Precipitation and temperature are directly provided by the records of the stations managed by the Spanish Agencia Estatal de Meteorología (AEMET) over the area. There have been considered all stations over the area studied when data records are available. Figure 36 shows the distribution of the meteorological stations over the Ter's basin. Each zone represented with the same colour represents an area with equal precipitation computed by means of the Thyessen polygon's method. There are also pointed out the control points used to calibrate the input flows. In the case of the Ter's basin there is found station EA033 managed by ACA at the upper area of the basin, which enable to calibrate the flows at a daily timescale and their monthly water volumes associated. The downstream part is controlled only at a monthly time scale using the contributions provided by the SIMGES model of Aquatool, which is used by *Agència Catalana de l'Aigua* in its Management plan for the river basin district of Catalonia, to verify if the results obtained by HBV model are consistent with the expected contributions.

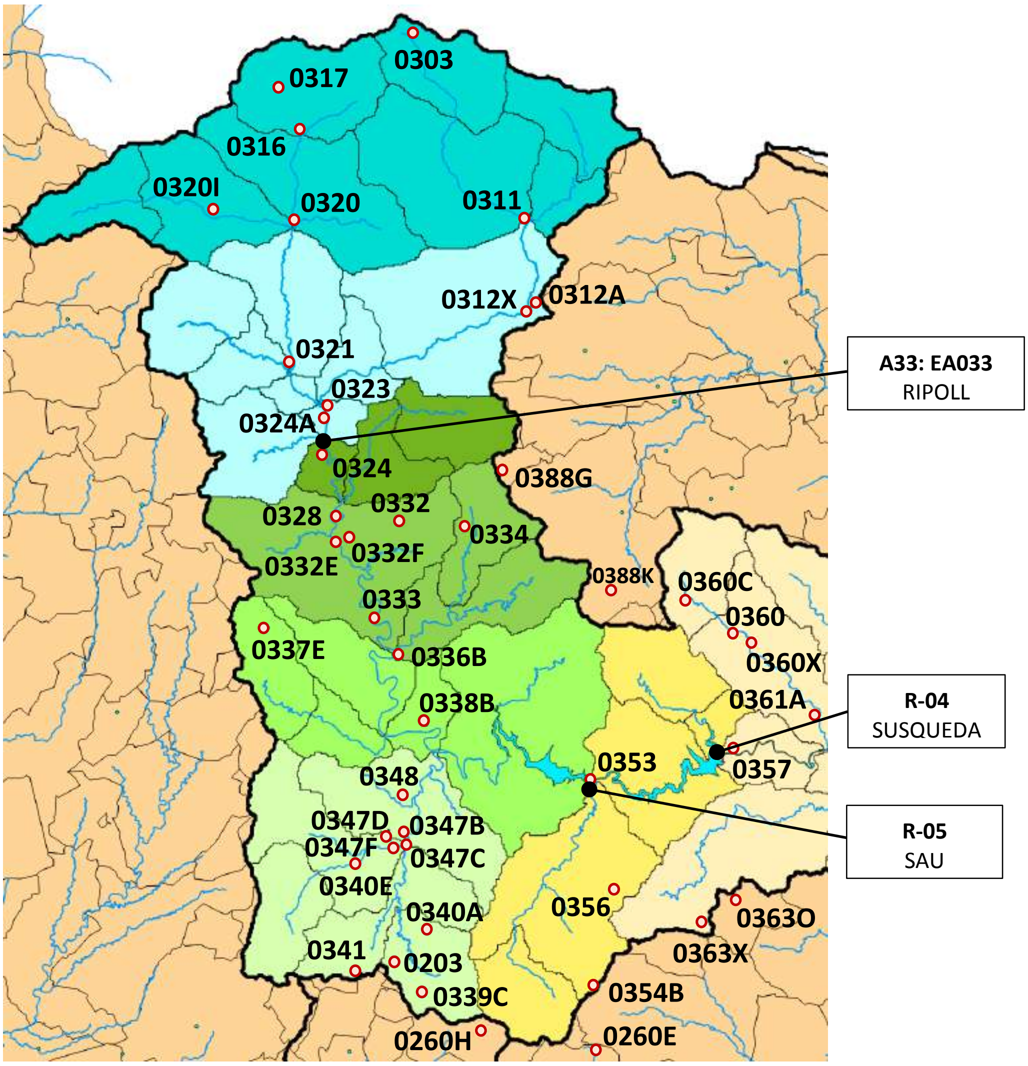


Figure 36: Sub-watershed division for the Ter's reservoirs.

Several aquifers are found over the study area (Figure 37). On the one hand, upstream the EA033 station there are found aquifer 110 [a3] characterized by its low permeability and aquifer 115 [a4] which is more permeable than the upper one. From EA033 station to the

Sau's reservoir there is another water body composed by different aquifers. However, since there is not any gauge station over the region, this area is considered as a homogeneous one with the same geological properties. This approximation is made due to the lack of data to verify daily results obtained (only at a monthly timescale) and considering that the contribution of the water volume of this region to the final amount that arrives to the reservoir is on average around the 25% of the total one, which enhances their high permeability and the importance of the upper region that can be adjusted with more precision.

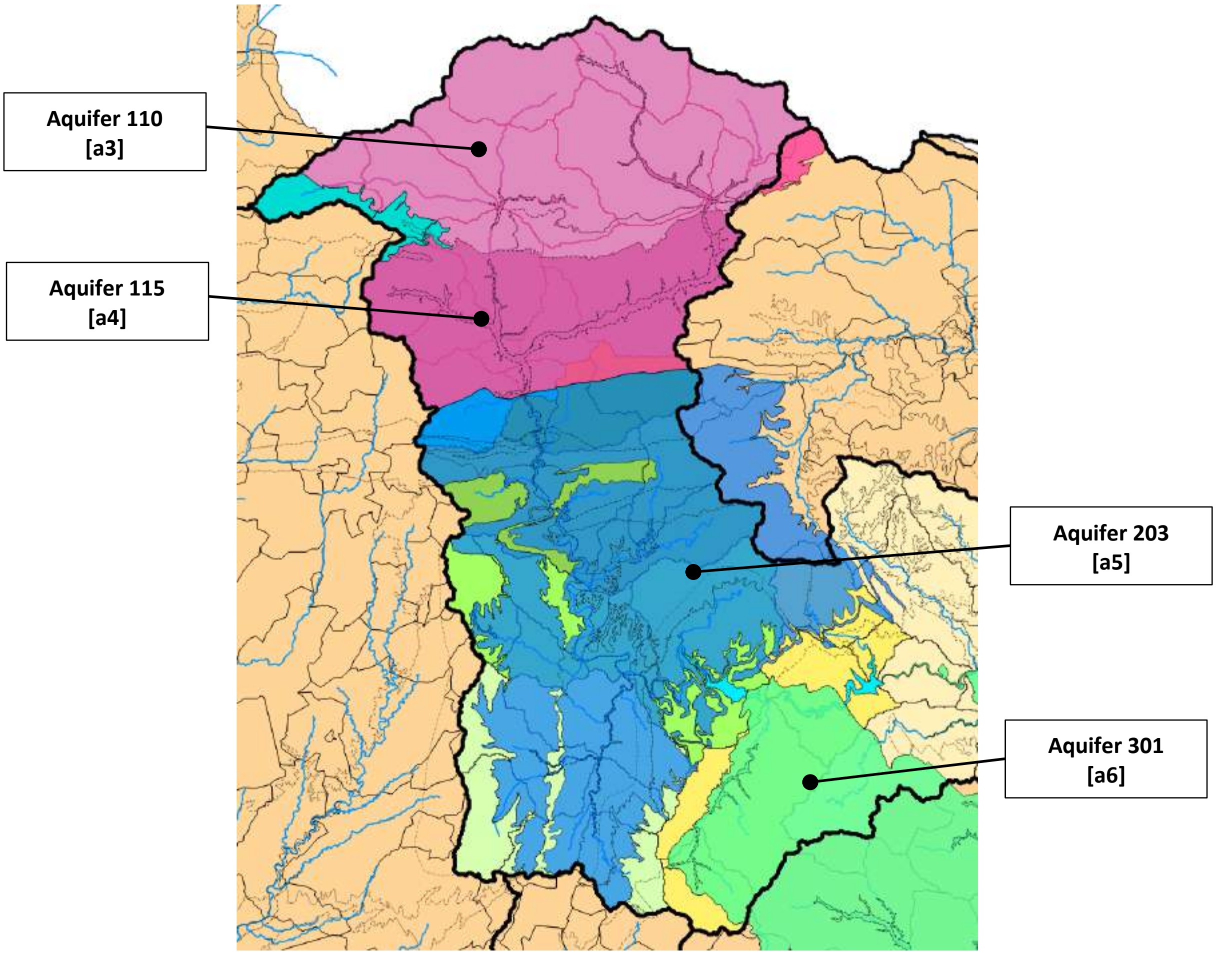


Figure 37: Aquifers over the Ter's watershed.

On the other hand, the Llobregat's basin is covered by several meteorological stations: EA078, EA087 and EA021. The total volume contribution that enters the dams are also compared with the values provided by ACA using the SIMGES model of Aquatool to check the computed amounts with the HBV model.

Aquifers of Llobregat's basin are formed basically by limestone characterized by a high permeability, and a marl and rocky piedmonts characterized by a low permeability. Three different aquifers are found over the study area, the rest of the sub-basins are considered as low permeability area. Aquifer 116 is denoted as [a1] whereas aquifers 112 and 115 have similar geological properties and so they have been considered as one [a2].

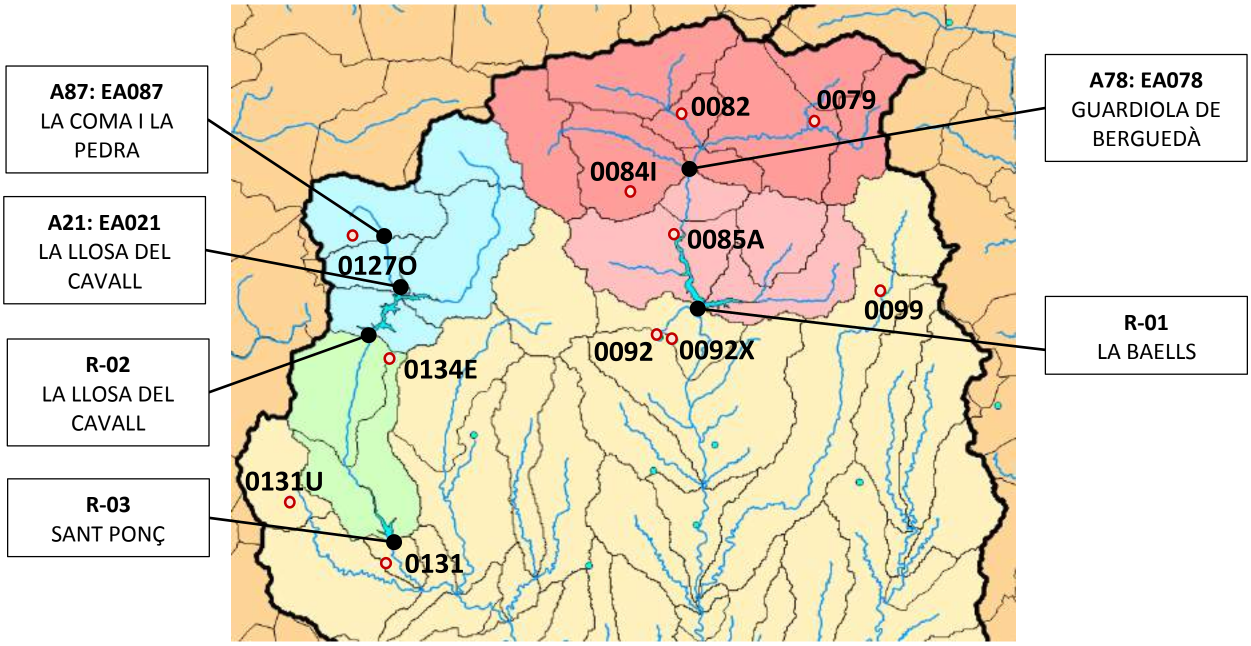


Figure 38: Sub-watershed division for the Llobregat's reservoirs.

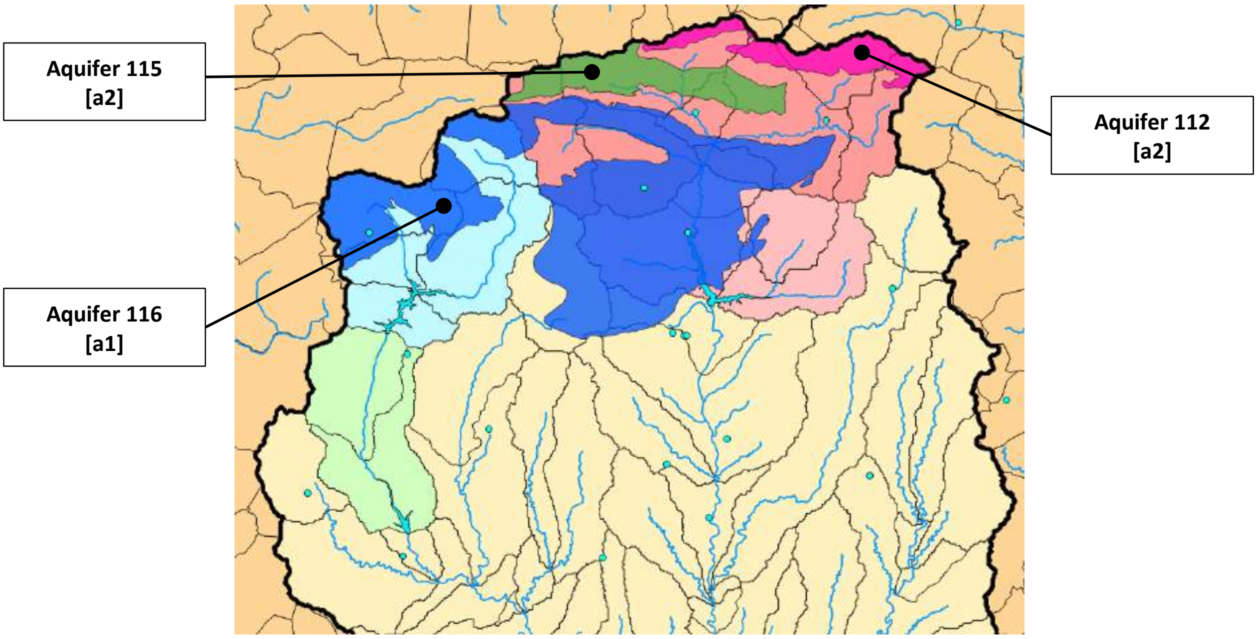


Figure 39: ***Aquifers over the Llobregat's watershed.***

Taking into account the information exposed, it is made the disaggregation proposal for each of the sub-basins contained in Table 13:

- **La Baells**: The basin is split in 4 sub-catchments. The ones contained into the A78 area include aquifers [a1] and [a2] as well as a low permeability area. The area R01 catches the flow coming from the upstream sub-catchments and adds its own contribution.
- **La Llosa del Cavall**: There have been considered 4 different sub-catchments. A87 and A21 represents the aquifer part [a1], also present in la Baells sub-basin. There are included two additional low permeability sub-catchments downstream.

- **Sant Ponç**: Two sub-catchments conforms the basin. In this case, there is not any aquifer over the area.
- **Sau**: The basin is split in 6 different areas. The ones located inside A33 region corresponds to the upper aquifers [a3] and [a4], which represents the 75% of the total contribution that arrives to the Sau's reservoir. Subcatchments 3, 4, 5 and 6 are simulated with the same properties but different precipitation and temperature data.
- **Susqueda**: Only one subcatchment is considered. Parameters are transposed from the [a5] aquifer and adjusted with the monthly contributions used as a reference.

Table 13: Disaggregation proposal for each sub-basin over the Llobregat and Ter basins.

River basin	Reservoir	Sub-catchment	Area [km²]
Llobregat	La Baells	1: A78: aquifer-[a2]	86.40
		2: A78: low.perm.	149.6
		3: A78: aquifer-[a1]	96.90
		4: R-01: reservoir	170.80
	La Llosa del Cavall	1: A87: aquifer-[a1]	25.30
		2: A21: aquifer-[a1]	49.10
		3: A21: low.perm	94.00
		4: R-02: reservoir	26.70
	Sant Ponç	1: R-03: low.perm	52.65
		2: R-03: reservoir	57.34
Ter	Sau	1: A33: aquifer [a3]	424.40
		2: A33: aquifer [a4]	312.50
		3: R-04: aquifer [a5.1]	76.40
		4: R-04: aquifer [a5.2]	205.60
		5: R-04: aquifer [a5.3]	249.80
		6: R-04: aquifer [a5.4]	259.40
	Susqueda	1: R-05: aquifer [a6]	245.30

The remaining input needed is the potential evapotranspiration (*ETP*), which accounts for the losses of the precipitation fallen. Potential evapotranspiration has been computed using the Thornthwaite formula (ETP_{raw}) and after it is applied a correction to adjust better the results obtained according to two parameters (ETP1 and ETP2) using the Penman evapotranspiration as a reference.

The output of the model is the response hydrograph obtained at the exit of each sub-basin. The area under the curve represent the water contribution that enters the dams in terms of water volume, which conditions the water availability. In order to check the suitability of the model at each sub-basin it is computed the water contribution at a monthly time scale for all the reservoirs between years 1980 and 2015. The results are compared with the ones provided by Agència Catalana de l'Aigua. Next figures shows the response hydrographs obtained at some points where stream gauge stations provide records. The response hydrograph simulates well the base flows but peak flows are not always catch properly. For some basins, at a monthly timescale, the HBV model underestimates the water contribution. The main reason that can be argued to explain this may come from the precipitation records, at high regions like this, convective storms may occur over a localized area not covered by any meteorological station. In any case, the HBV contributions are on the security side. The values of the SIMGES model contributions used by ACA in its water management plan are also smaller and closer to the ones computed by the HBV. Thus, the response of the HBV model is quite reasonable.

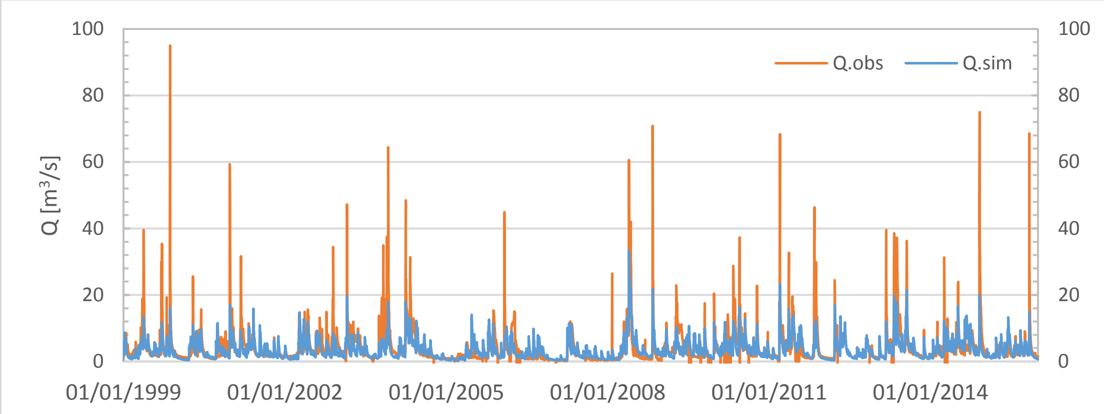


Figure 40: EA078: Observed and computed response hydrograph (Guardiola de Berguedà). [Upper graph: Flow in m^3/s / Lower graph: Monthly contribution in hm^3].

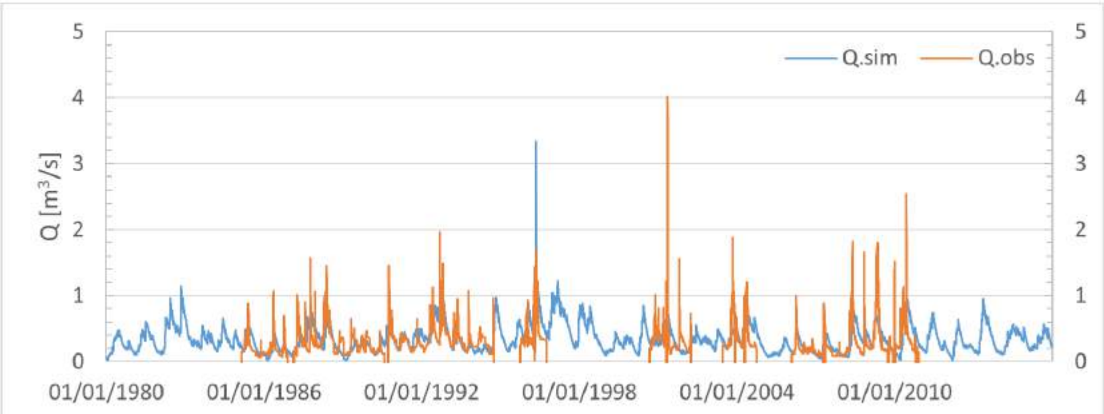


Figure 41: EA087: Observed and computed response hydrograph (La Coma i la Pedra). [Upper graph: Flow in m^3/s / Lower graph: Monthly contribution in hm^3].

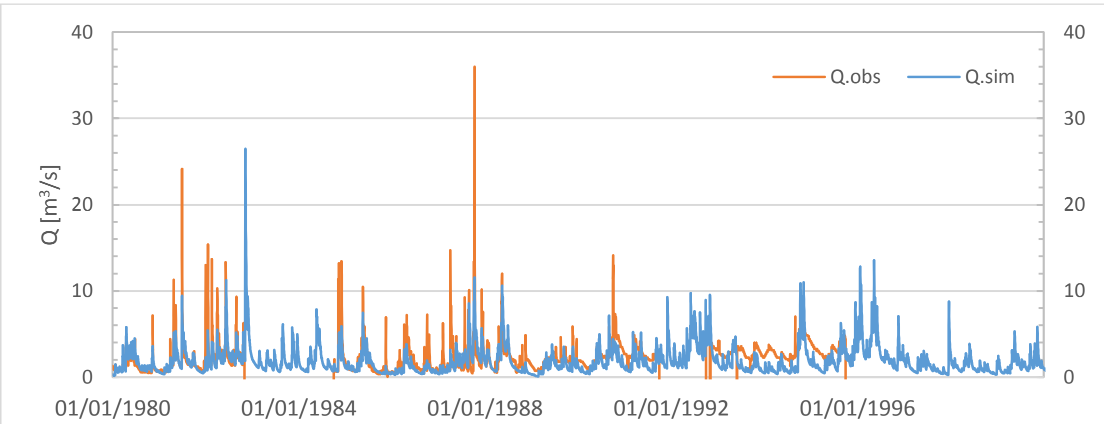


Figure 42: EA021: Observed and computed response hydrograph (La Llosa del Cavall). [Upper graph: Flow in m^3/s / Lower graph: Monthly contribution in hm^3].

Llobregat river water turbidity model

Barcelona and its metropolitan area gather more than three million people. Water distribution is ensured by Aigües de Barcelona, mainly using water sources from the basins of the Llobregat and Ter rivers, and alternative water sources such as the desalination plant of El Prat de Llobregat. Over the years, urban and industrial pressure had been modifying the nature of the basin. As a high populated region, the production of wastewater is also high. Catalan authorities frontload efforts to reduce the consequences to the environment with restrictive laws. The economic investments made to improve the sewage networks or constructing new water treatment plants, among others, as well as the development of a social environmental awareness have made possible to achieve important improvements during last years. In the Llobregat basin, both surface water and underground water are used. Usually surface water is the main source. Two drinking water treatment plants (DWTP) treat the water of the Llobregat before its distribution to the population, one in Sant Joan Despí and other in Abrera.

The Llobregat's river originates in Fonts de Llobregat (Castellar de n'Hug), at the south of the Catalan Pyrenees. Throughout its development receives the water from several tributaries, the most important ones are the Cardener's river, Gavarresa's stream, the Anoia's river and the Rubí's stream. Water quality of the river comes determined by urban and industrial discharges made directly into the Llobregat or indirectly into any tributary. Nevertheless, despite all the efforts made by the Catalan water management entities, the rivers of this basin are still characterised by its low quality. According to the Water Management Plan developed by Agència Catalana de l'Aigua in 2015, Catalan rivers, especially those ones located near most populated regions where human pressure is high, still have a low quality.

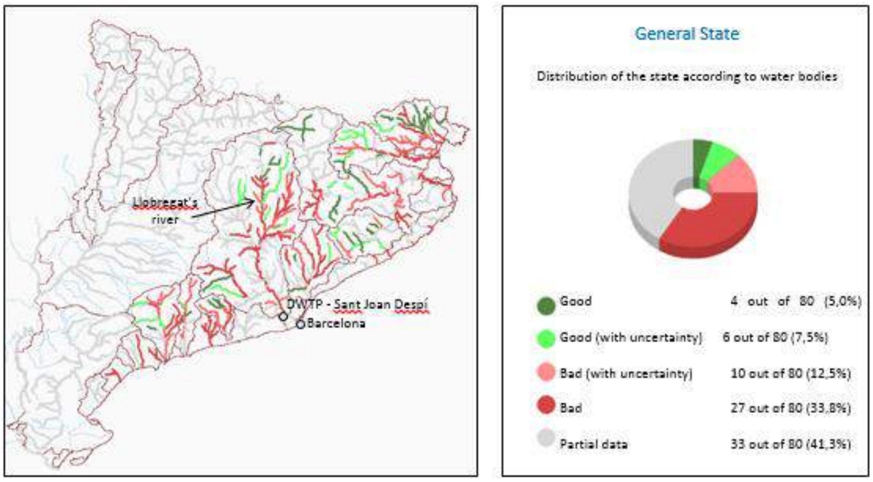


Figure 43: General state of the water bodies in Catalonia [Data 2013-2015]. The classification of each state depends on several requirements that accounts for ecological and chemical state. *[Source: Catalan water agency - ACA]*.

Different consequences are derived from this reality, involving ecosystems, water uses, etc. One of the most worrying is referred to the drinking water production. For the particular case of Barcelona and its metropolitan area, an important part of the water used to serve the city (almost the 50%) comes from the Llobregat's downstream section, concretely at the drinking water treatment plant (DWTP) of Sant Joan Despí.

In spite of all, the water produced in the DWTP of Sant Joan Despí has a very high quality. The plant has a sophisticated configuration to accomplish with all standards defined in the Spanish law RD 140/2003 that establishes the health quality criteria for drinking water. Around 300.000 m^3 of water coming from the Llobregat's river are treated every day. Once the water enters the plant, it is applied a pre-treatment consisting of pre-oxidation with chlorine dioxide, coagulation/settling and filtration with sand. This water feeds two different production lines. One applies a conventional treatment (ozonisation and activated carbon filters) and the other an advanced treatment (ultrafiltration and reverse osmosis). After remineralisation both effluents are mixed providing the final outcome.

The water quality of the river is one of the most determining key points in the treatment carried out inside the DWTP. The cleaner the river is, the easier the treatment will be, which means that more water can be treated which less effort and time. In the DWTP of Sant Joan Despí (SJD), it is analysed the water of the Llobregat's river, at the catchment of the plant. The indicators measured must be under a certain threshold to guarantee a proper treatment in the DWTP. Otherwise, the plant is not able to produce drinking water from the river. When this happens, water supply is entirely covered by the water pumped from wells, nevertheless the amount of the resource that can be used is limited because it entails the decrease of the aquifer levels. The use of this water is actually cheaper than the superficial one because pre-treatment is no longer necessary although the production flow decreases.

There are different parameters that characterise the water quality, one of them is the turbidity, defined as the cloudiness of the liquid caused by the micro-particles contained in the water. Turbidity is measured in nephelometric units (NFU) which quantify the light intensity scattered at 90 degrees from an incident light beam thorough the water sample. It is well known by the operators of the DWTP of Sant Joan Despí that one of the determining parameters which affects the turbidity level is the precipitation. Based on their observations and expertise, they realise that when a rainfall event occur over the Llobregat's basin, especially at the downstream parts, it is expected that turbidity measured in Sant Joan Despí increases. Besides turbidity, there are other pollutants that may affect the water quality of the Llobregat (Ammonium (mg NH_3/l), total organic carbon - TOC (mg C/l), and conductivity (µS/cm)). Ammonium and TOC directly depend on the discharges made by municipalities and industries into the river upstream Sant Joan Despí, whereas turbidity is caused by the precipitation over the basin. On the other hand, conductivity, an indirect measure of salinity, is not a main problem for the DWTP and rarely times inadmissible levels for this parameter are reached. High saline episodes are linked to the rupture of a brine collector that comes from el Bages, where salt mines are exploited, to the Mediterranean Sea following the river. Nevertheless these ruptures are not linked to any climate variable and the affections caused has a local character over the zone where the discharge takes place, but usually it does not have consequences in the DWTP of Sant Joan Despí.

All these parameters should be under a certain threshold, when an "alert" value is detected, the sampling frequency decreases in order to study with more accuracy its evolution and, in case the maximum enabled threshold is reached, the DWTP closes the water intake to avoid the entrance of polluted water inside the plant. Until mid-2014 the control analysis were made in a lab by the operators of the plant, on average, every 2 hours under normal conditions for ammonium and turbidity and every 4 hours for TOC and conductivity. In 2014 an automatic station became operational which reduced the sampling frequency to 1 hour.

Concerning the turbidity, the maximum acceptable value for the water at the catchment is 500 NFU under normal conditions and 1000 NFU in drought periods. When a high turbidity episode occurs, it is preferable to close the water intake during the time that turbidity limits in the river are unacceptable. High turbidity episodes can last from several hours until two or three days, depending on the precipitation distribution over the time. The turbidity problem is detected at hourly time scale, this means that to conduct an accurate analysis, it is important to know how the distribution of the precipitation along a day is. In this study, since the available precipitation measurements provided were daily records, the time scale considered for the turbidity estimation is also daily.

In order to understand the scope of the study, in Figure 44 it can be observed the flow and the turbidity of the Llobregat measured at the catchment of the DWTP of Sant Joan Despí as well as the average precipitation recorded over the Llobregat's basin between 03/11/2011 and 05/11/2011. Looking to the hydrograph there are detected three different peak flows (Q_{peak}) between 03/11/11 and 04/11/11 which means that three rainfall episodes took place during these days inducing a certain increment on the water turbidity. For the first event (green) precipitation should have fallen during the second half of the day, after 03/11/11 - 12:00 pm, causing a peak turbidity (T_{peak}) equal to 21000 NFU. For the second event (red) the peak flow arrives at 04/11/11 - 01:20 am, therefore the precipitation that caused this episode fell in the time period between 03/11/11 – 20:15 and 04/11/11 – 01:20, but it is not possible to quantify how much neither how long precipitation was. The rest of the precipitation P_{d2} felt during 04/11/11 causing the third episode (blue). Taking into account the limitations exposed, for each daily precipitation record, it is considered one turbidity increment induced, computed as the difference between the minimum and maximum T_{peak}. In those cases when two different turbidity episodes take place, it is considered the highest one, so that the worst situation is considered. As it will be seen afterwards, numerical values for the turbidity are not predicted, only the expected thresholds between these increments would be. In spite of all, it is a first step that may help to improve the operation of the DWTP of SJD and also the results can be used to make estimations for the different future scenarios (RCPs).

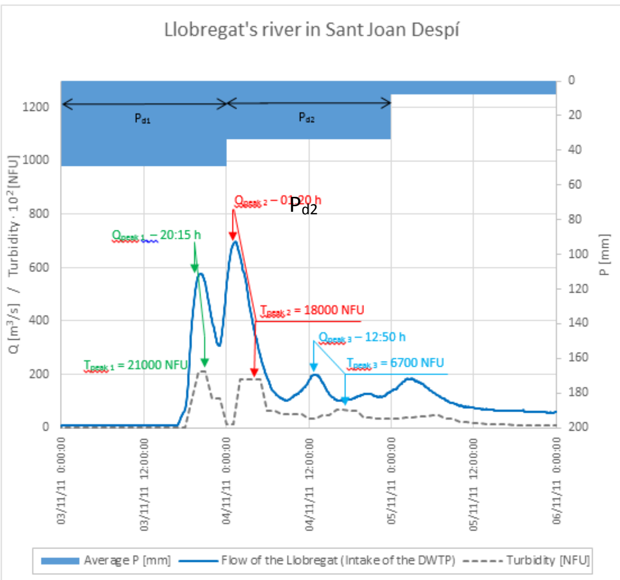


Figure 44: Turbidity and flow records in the Llobregat's river in Sant Joan Despí and daily average precipitation over the Llobregat's basin between 03/11/2011 and 05/11/2011.

On the other hand, as mentioned before, ammonium and TOC does not depends on precipitation but on human discharges (municipalities and industries). For the particular case of the Llobregat's river and the DWTP of Sant Joan Despí, human action has modified the natural regime of the tributaries of the river, which has direct consequences on the water quality at its downstream section. Nowadays, the Anoias's river and the Rubí's stream, two of the main Llobregat's tributaries, are deviated from its natural destiny to prevent their waters from reaching the river before Sant Joan Despí, where it is located the DWTP. Water of both rivers is conducted throughout different channels and it is discharged into the Llobregat, downstream the water intake of the DWTP, and finally reaches the Mediterranean Sea. The main reason to justify this river diversion is that both water bodies are traditionally highly polluted due to urban and industrial pressure (high ammonium concentration and total organic carbon). Intense rainfall episodes can make the diversions fail and so, the polluted waters from Anoia and la riera de Rubí reach the Llobregat before Sant Joan Despí. This may cause some inconveniencies in the DWTP because if the Llobregat's water is much polluted there is no way to treat it and the catchment must be closed.

The main objective of the Llobregat water quality model developed in RESCCUE is to establish a relationship between the precipitation fallen over the Rubí's sub-basin and the failure of the river diversion to feed the plant. Once this is done there will be analysed how does it influence the water quality of the Llobregat's river. Combining the turbidity generated by precipitation over the Llobregat's basin and the discharges made by the Rubí's stream directly into the river, it is expected to obtain a rough prediction of the evolution of the water quality just analysing the precipitation action over the whole basin.

The study area corresponds to the Llobregat's basin. Over this watershed there are available some precipitation gauge stations managed by AEMET which provide daily precipitation records. Figure 45 shows the Llobregat's basin and the location of the precipitation gauge stations where there are available records between years 2010 and 2015. The rest of the watershed does not contain information between the time period studied.

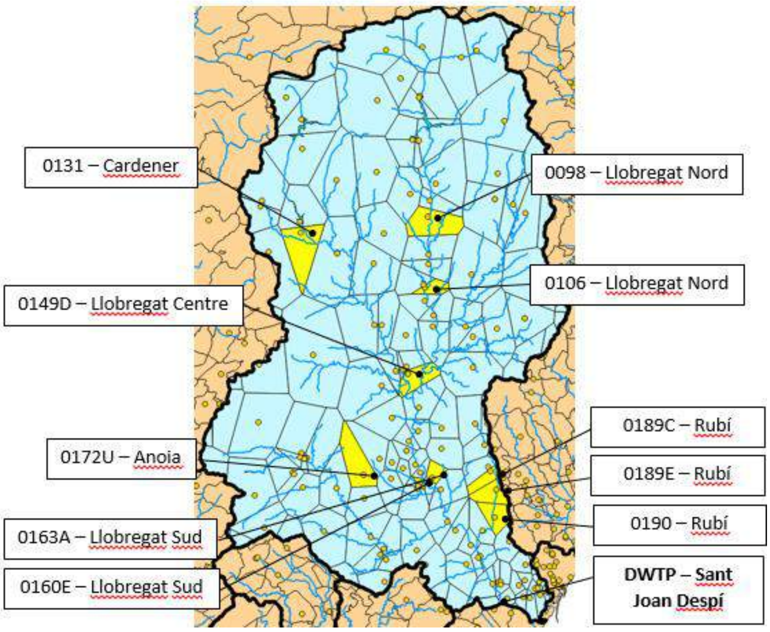


Figure 45: Precipitation gauge stations over the Llobregat's watershed.

In broad terms, it is observed that those days when the precipitation is high, turbidity level in water increases. Intense precipitations cause the erosion and the movement of the particles accumulated on the river bed making the turbidity levels rise. However not always a high daily precipitation provokes inadmissible peak turbidity levels, so it is needed to look at the big picture and characterise the precipitation according to its magnitude and spatial distribution (precipitation patterns) and look the turbidity induced each day. The methodology applied to find a correlation between rainfall and turbidity is based on the use of a set of statistical indicators, which enable to characterize the properties of the recorded precipitation and define several precipitation patterns. These patterns are associated to a certain turbidity increase and the objective is to establish a probability of occurrence for each of them.

Turbidity samples analysed are the measurements done at the catchment of the DWTP of SJD between years 2010 and 2015. For each day will be established the precipitation measured (precipitation pattern) and the maximum turbidity level reached in the water. In order to carry out the analysis, four turbidity levels were defined:

1. No T: No increment on the turbidity was observed
2. $0 < \Delta T < 500$ NFU
3. $500 \leq \Delta T < 1000$ NFU
4. $\Delta T \geq 1000$ NFU

On the other hand, the use of "average" precipitations as indicators enables to distinguish easily between episodes where the recorded rainfall has been significant all over the basin and the cases when it has had a local character. In addition, due to the fact that the catchment in SJD is located at the downstream part of the watershed, the precipitation recorded in the southern stations, (and so closer to the DWTP) have a stronger influence on the water turbidity than those located at the North. Therefore, combining the indicator "Average [South]" with the maximum precipitation "*P.max [South]*" it is possible to have an idea of the magnitude of the rainfall event. Finally, 5 rainfall patterns have been established and Table 14 summarizes the thresholds imposed for all of them.

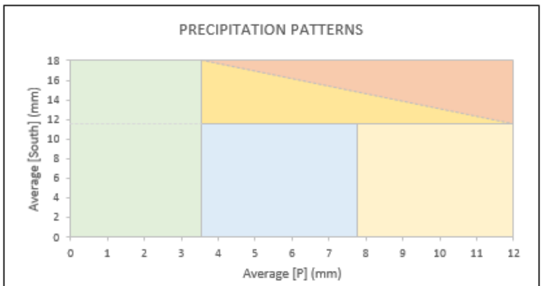
Table 14: Precipitation patterns.

	Average [P] (mm)	Average [South] (mm)	P.max [South] (mm)
Pattern 1	≤ 3.55	-	-
Pattern 2	3.55 < x ≤ 7.77	≤ 11.56	-
Pattern 3	> 7.77	≤ 11.56	-
Pattern 4	> 3.55	> 11.56	≤ 27.80
Pattern 5	> 3.55	> 11.56	> 27.80

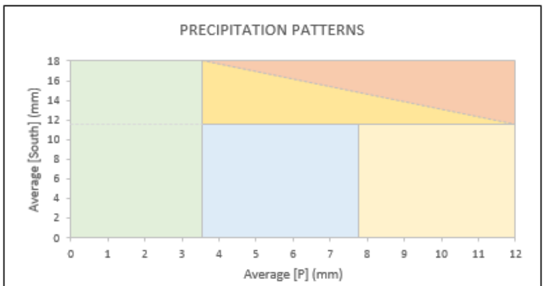
- Pattern 1: Includes all the days when the precipitation is null or very low in all the stations of the watershed. Therefore the expected increment in the turbidity measured in the catchment of SJD is null.
- Pattern 2: Rainfall is low in all the stations, sometimes even null in some of them, especially in the southern area, but there may be local high precipitation episodes which cause a considerable increase in the turbidity. Nevertheless the most common behaviour is not have problems in SJD.

- Pattern 3: The rainfall characteristics are similar to the Pattern 2. The main difference is that there may be such a high precipitation over the northern area of the watershed that cause increments in the turbidity up to 500 NFU, in some cases even more.
- Pattern 4: Rainfall is considerably high over the whole watershed. However, the most intense one falls over the southern area of the watershed. This pattern is always associated to an important increment in the turbidity measured in SJD. Almost the half of the times this increment exceeds 1000 NFU.
- Pattern 5: This pattern is similar to pattern 4, the main difference is that very high precipitation episodes take place over the southern part of the watershed. These episodes always induce increments in the turbidity higher than 1000 NFU causing inadmissible turbidity levels in the catchment of SJD.

The identification of the precipitation patterns helps to predict the turbidity levels expected in water. Figure 46 summarizes the results extracted from the study. For the turbidity's prediction there must be took into account the precipitation measured over the whole Llobregat's basin at the AEMET stations, whereas to estimate the failure of the Rubí's diversion only are needed three stations: 0189C – 0189E – 0190. Both graphs complement each other. On the one hand, the turbidity patterns enable to make an estimation of the turbidity levels that would be measured in the Llobregat's river at the catchment of the DWTP of Sant Joan Despí (critical levels are established at 500 NFU). Moreover, if the Rubí's deviation fails, it is ascertained that the 88% of the times there will be a decrease of the water quality at the catchment of the DWTP due to ammonium, TOC or turbidity, thus, the plant would have to close the water intake during this day and be out of service until acceptable levels are reached again.



Turb. level	ΔT = 0 NFU	0 < ΔT < 500	500 ≤ ΔT < 1000	ΔT ≥ 1000
PATTERN 1	99.80%	0.20%	-	-
PATTERN 2	58.10%	30.10%	11.80%	-
PATTERN 3	7.70%	66.70%	10.30%	15.40%
PATTERN 4	-	30.60%	25.00%	44.40%
PATTERN 5	-	1.80%	3.60%	94.50%



Turb. level	ΔT = 0 NFU	0 < ΔT < 500	500 ≤ ΔT < 1000	ΔT ≥ 1000
PATTERN 1	99.80%	0.20%	-	-
PATTERN 2	58.10%	30.10%	11.80%	-
PATTERN 3	7.70%	66.70%	10.30%	15.40%
PATTERN 4	-	30.60%	25.00%	44.40%
PATTERN 5	-	1.80%	3.60%	94.50%

Figure 46: Turbidity prediction in Sant Joan Despí (on the left) and prediction of failure for the Rubí's river diversion (on the right) on the basis of rainfall patterns.

Conclusions of the Barcelona case study

The case study of Barcelona analyzed the impact of multi-hazards derived mainly form the water management sector like urban flooding, CSOs, water supply, etc. This chapter presented the so-called sectorial and integrated models used to simulate all the different hazards analyzed. Also, the results of the baseline scenario that corresponds to the actual situation are shown.

The 1D/2D urban flood model that was calibrated and validated based on observations during 4 different flood events, was used to simulate spatially distributed maps of maximum flood depths and velocities during design storms events of different return periods (2, 5, 10, 100 and 500).

The outputs of the 1D/2D model are used to compute:

- Hazard maps for different rainfall return periods for pedestrians and vehicle safety, and for waste containers stability based on hazard and stability criteria;
- Maps of traffic interruption and traffic affections in terms of reduced velocities for different return periods;
- Maps of electrical infrastructure affected for different return periods;

These modeled hazards will be used to evaluate future scenarios and adaptation measures.

The bathing water quality model was also calibrated and validated to simulate the mean number of days per bathing season that sea water would not comply with bathing water quality standards due to the presence of CSOs. This model will also be used to evaluate future scenarios and adaptation measures.

All the other models will be used to evaluate current and future scenarios: the sea level rise model, the pipe burst model, the drought model and the Llobregat river water quality model.

5. Multi-hazard assessment for the Bristol Research Site

The estimated population of Bristol in 2016 was 449,300 making it the eighth most populous city in the UK. Bristol is located in the south-west of England near to the Severn Estuary and the Bristol Channel. There are two major rivers flowing through Bristol, the River Avon and the River Frome. Due to the proximity to the sea (Severn Estuary), the River Avon is influenced by the tide throughout Bristol.

The flow of water through Bristol is heavily influenced by the topography. The northern and southern extents of the city are located on high ground that both slope down towards the city centre. Therefore the rivers in the north and south follow this topography and flow down to the River Avon, which defines the lowest lying areas of the city. The most northerly extent of Bristol, in the vicinity of Avonmouth, is also low lying as it is located on a coastal plain of the Severn Estuary.

As an island nation with temperate maritime climate the UK is prone to variable weather conditions. These are influenced by weather systems from the North Atlantic Ocean and from mainland Europe. Conditions at sea are particularly influential on the weather experienced in the southwest of England, where Bristol is located. In Bristol Atlantic depressions and convection systems are the causing factors for the rainfall formation. Around autumn and winter is when the Atlantic depressions exude their most significant impacts and most rainfall is attributed to this source. The convection systems are more typical in summertime, during the hotter months, and formed by solar surface heating. The thunderstorm clouds this produces are more sporadic and isolated in nature yet typically more intense and unpredictable. Rainfall in Bristol is fairly persistent and consistent throughout the year, with 170-180 days of rain over 0.2 mm, 120-130 days of rain over 1.0 mm and 25-30 days of rain over 10.0 mm. The average annual rainfall in Bristol lies between 800-900 mm and autumn and winter are slightly wetter seasons. There is variation with this though with a notable increase from the north to the south of the city. In north Bristol the average annual rainfall range tends to be lower, at 600–900 mm, whereas in comparison to south Bristol where it is higher at 900 – 1,200 mm. Altitude could be attributed to this. The hillier areas in the south force moist air to ascend the higher topographic land causing the cooling effects and producing condensation and rain formation. December and January see the most rainfall in Bristol while April to July is the driest. The main change in influential weather systems being from the Atlantic depressions when the sea is warmer to when it is cooler and the Azores high pressure system takes over. 2012 was observed as the wettest year on record in the UK. In recent years there have been wetter, milder winters with hotter, drier summers. So the effects of climate change may therefore already be apparent and noticeable in Bristol and the UK.

1D/2D Urban Drainage model

Like most long-established cities, the sewerage system in Bristol has been extended to serve the growing population. The original (pre-1850) sewers were little more than culverted watercourses draining to the River Avon. The period 1880-1914 saw a rapid growth in urbanization and many of the sewers within the city centre date from this period. The great majority of Bristol is served by a combined (foul and rainwater) system, however the more recent developments (post-1970) served by separate systems draining to local watercourses. Only about 24% of the Greater Bristol urban area is served by true separate (foul and surface-water) sewerage; the remainder is either fully or partially combined. The sewerage network serving Greater Bristol (including outlying areas in South Gloucestershire) drains to a large sewage treatment works (STW) located at Avonmouth and discharging treated effluent to the Bristol Channel; this STW serves a resident population of 671,000, plus trade effluent equating to 44,000 population equivalent.

For the purposes of sewerage and drainage planning, the city is broken down into a number of drainage areas, of which nine are within the city of Bristol and a further four are within South Gloucestershire, but flow from these ultimately drains into the city sewers for treatment at Avonmouth STW. The research site is with the Malago Drainage Area. The Malago Drainage Area Plan document (initially prepared in 1996) provides comprehensive information about the nature, function, condition and performance of the sewerage network, although all of the key information is continually updated and is now presented on the Wessex Water corporate GIS system. Whilst most of the Bristol system drains by gravity, there are several pumping stations, the largest of which is Ashton Avenue pumping station which is within the Ashton Vale research site area.

The scope was to develop a citywide Surface Water Management Plan (SWMP) model. The objective of this was to identify the areas of highest risk of pluvial flooding. This was formed utilizing a combination of an established 1D sewer network model and a new 2D detailed ground surface model. The model allows storm rainfalls covering a wide range of storm return periods to be superimposed on the drainage network; the likely impacts of climate change can also be allowed for within the storm rainfall generator embedded within the model. Where the sewer capacity is exceeded, flooding out of a manhole and routing of the flow across the terrain to re-enter the drainage network can be simulated, which is a real benefit of this analysis. Such a model allows true cause and impact analysis of flooding. Drainage planning is well-established within Wessex Water and Bristol City Council and there has been continuous improvement and enhancement of the sewerage model over the last 30 years, in line with software development, industry requirements and best practice. The sewerage model has been regarded by Wessex Water as an essential planning and design tool over this period. As it currently stands, the current city-wide Bristol *Infoworks ICM* model includes:

- 448,070 “nodes” (e.g. inlets, junctions, manholes etc)
- 239,514 manholes
- 407,271 “conduits” (i.e. discrete pipe or open channel lengths)
- 48 pumping stations (including variable speed pumps)
- 11 storm tank structures (including on-line tunnel storage)

- 278 Combined Sewer Overflows (CSOs)
- 23 siphons (conveying sewage beneath rivers, Bristol Harbour etc)
- Domestic flow from 289,951 properties
- 165 trade effluent discharge inputs
- Representation of Avonmouth STW, including inlet screw pumps, storm tanks, overflow and storm tank return pumps
- Real-time control representation of major pumping stations and controls

The entire base data used to construct the model is held in various layers on the Wessex Water corporate GIS system. Two strategic capital schemes are currently underway which will impact upon the performance of the entire Bristol catchment. These are:

- The Frome Valley Relief Sewer Phase 3 (a 1.2 to 1.8m diameter tunnel taking flows from the north of Bristol towards the STW) – this will reduce peak flows through central Bristol during times of storm, reducing flooding and CSO discharges. Completion in October 2018
- The Trym Tunnel (a 2.85m diameter tunnel taking flows from west Bristol towards the STW) – this will provide capacity for long-term development and will further reduce flow through central Bristol. Completion in Autumn 2022.

Figure 47 shows the extent of the Bristol catchment and shows modelled sewers (both combined and surface water). The most up to date version of the Wessex Water UPM (detailed) base model was used for the research site. This covers the entire Avonmouth catchment (i.e. city-wide) and underwent review prior to update. This included amendments to the surface water systems. A key factor in the update was applying sub-catchments to simulate foul/combined water and surface water flows to ensure they are modelled appropriately. The hydrological (surface runoff) catchments were defined by using the Flood Estimation Handbook methodology with topographic data, in line with UK water industry best-practice recommendations. Streams and watercourses were represented in the 2D model as a channel in the terrain "mesh".

While the 1D sewerage model was applied city-wide, the 2D modeling of flows across the urban surfaces was done in seven distinct hydrological catchments, using the same baseline 1D model. The extent of the area containing the Ashton Vale research site is shown in the model plans following (Figure 48 and Figure 49).

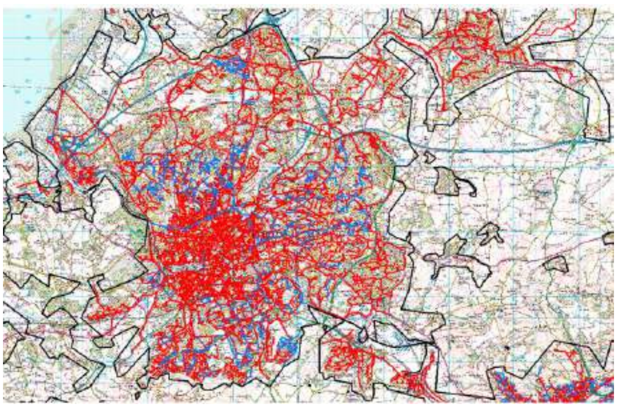


Figure 47: Extent of the Bristol catchment showing modelled sewers.

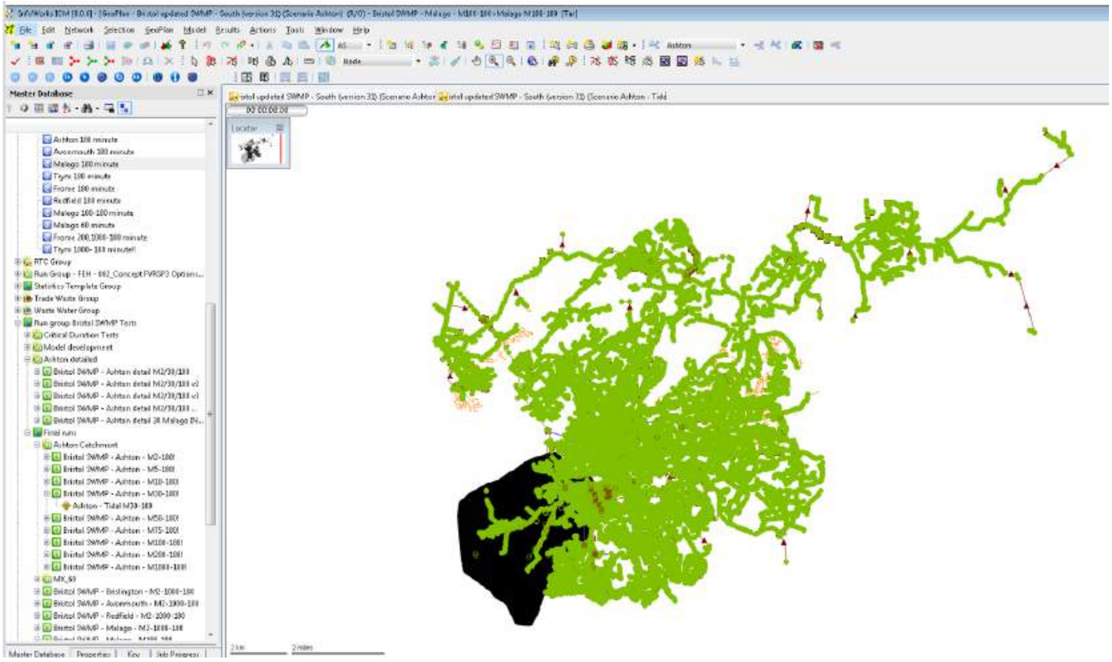


Figure 48: Extent of the Bristol model containing the Ashton Vale research site.

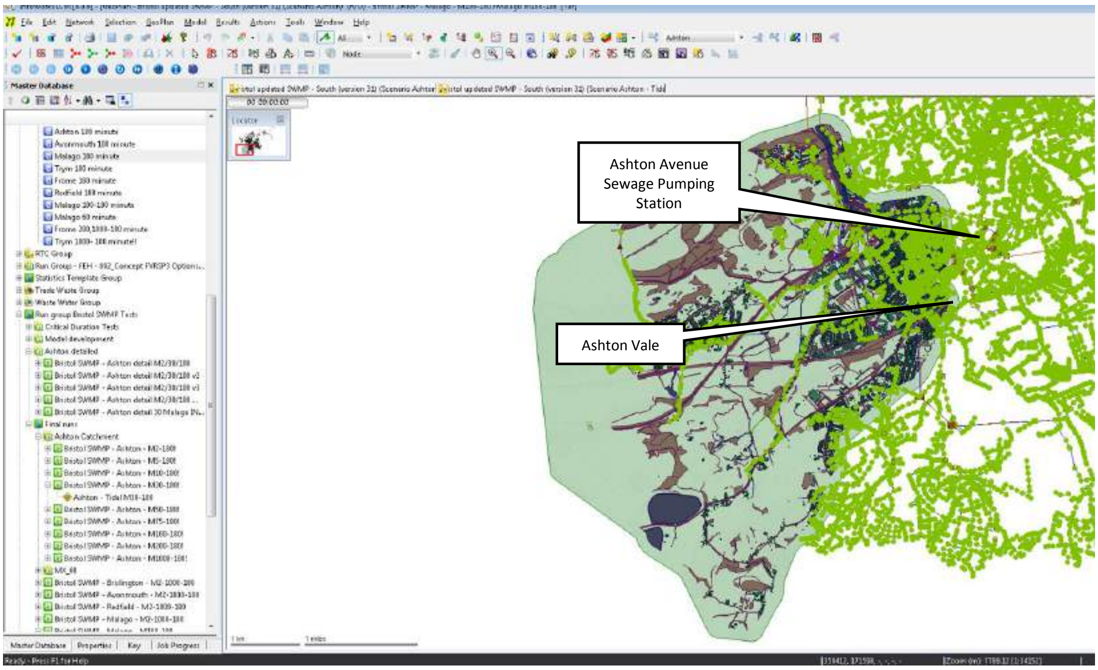


Figure 49: Extent of the area containing the Ashton Vale research site (hydrological catchment).

A 2D mesh was generated and this used infiltration zones to evaluate losses across the model, taking account of the nature of the urban surfaces and soil type /permeability. Direct rainfall analysis was used throughout and any associated losses accounted for. The triangular meshes were developed further using detailed mapping from Master Map info, thus allowing buildings, roads and railways to be identified. The model extract in Figure 50 below shows the fine mesh together with the modelled sewers, overlain on roads, buildings and urban features.

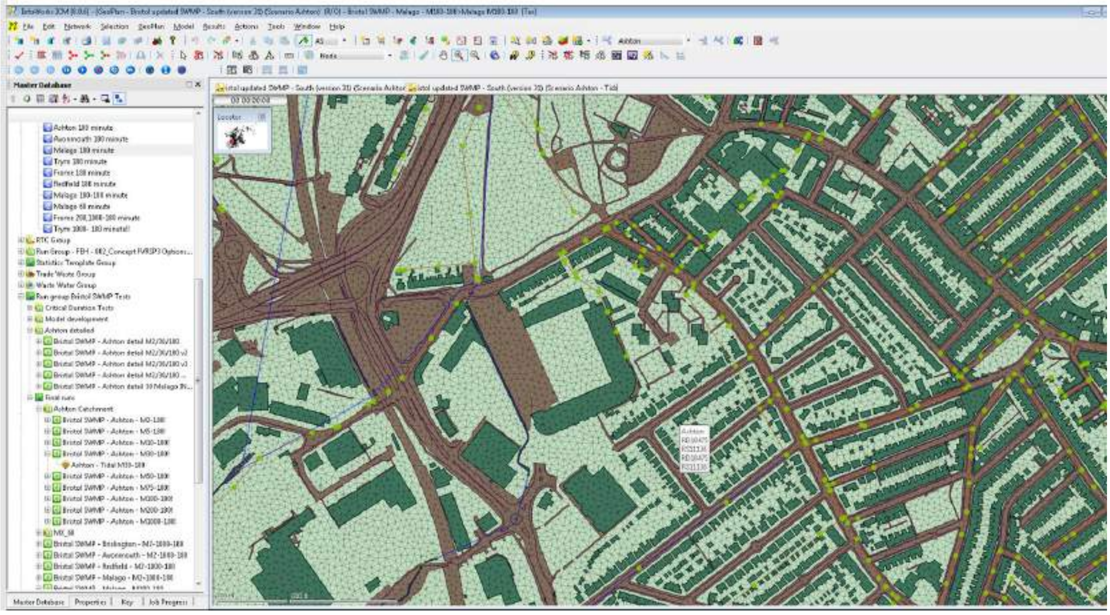


Figure 50: Model extract showing the 2D "mesh" for routing flows over urban surfaces.

The succeeding versions of the sewerage model have been verified against flows measured within the sewer, under both dry weather and storm conditions. Individual flow (depth-velocity) monitors typically measure and record flow at 2 minute intervals and would be in place for a period of between 6 and 12 weeks in order to catch adequate stormflow response data, with rainfall recorded by a network of raingauges deployed across the catchment (also measuring rate of rainfall at 2 minute intervals). Raingauge data is supplemented by continually recording "weather radar" rainfall data provided to Wessex Water by the UK Met. Office.

Across the Bristol catchment as a whole, flows have been measured at over 350 individual locations by means of temporary flow monitors. Within the Ashton Vale study area, flows have been monitored at some 37 individual locations on both the combined and surface water sewerage systems. In addition to temporary flow measurement, the permanent telemetry systems within the sewerage network (including all pumping stations and significant combined sewer overflows (CSOs)) provide a means of continuous flow data acquisition to provide further confidence in model verification.

In addition to verification against measured stormflows in response to measured rain, the model has also been verified against observed flooding incidents. Wessex Water has detailed knowledge of the location of flood-prone areas, gained through local observation, operational incidents and also from reports called in by customers (residents). All customer contacts are recorded on an incident database (termed "RAPID") and these are displayed on the corporate GIS system, allowing "cluster analysis" of incidents – including internal and external flooding, pollution, sewer blockages etc.

These flood flows, plus surface runoff and flows flooding from watercourse channels is routed by the Infoworks 2D model across the terrain "mesh" to generate the flood predictions as shown in the example below (Figure 51).

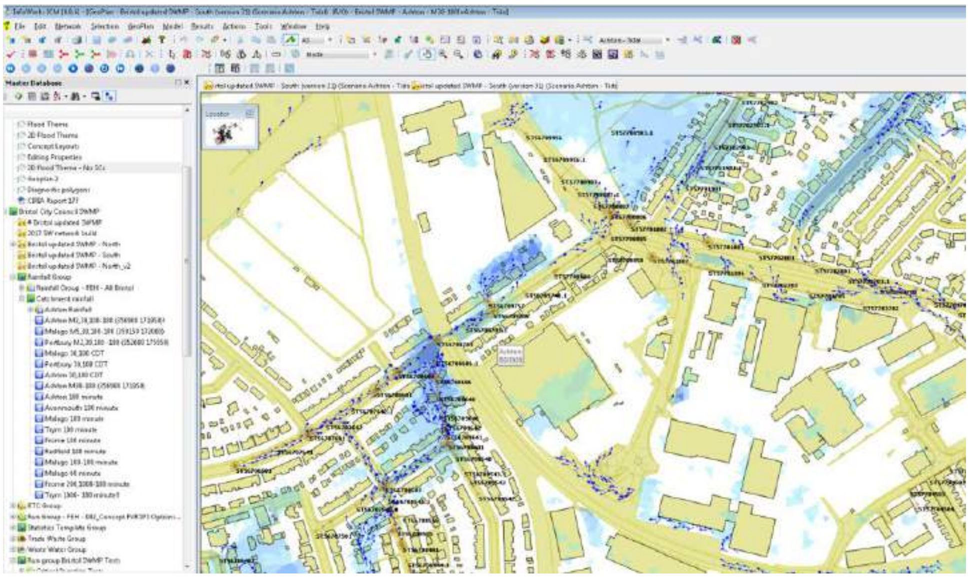


Figure 51: Example of flood predictions from 2D modelling, showing flow directions and ponding of flows.

Flow paths across the terrain are shown by arrows and the flood prone areas are indicated in blue (the shades of blue indicating flood depths of 0.1-0.3 m, 0.3-0.6 m, 0.6-0.9 m and > 0.9 m). Surface flow velocities can also be superimposed on the plan, however in the Ashton Vale area the flow velocities for extreme storm events are generally below 0.25 m/s and never exceed 0.5 m/s due to the flat terrain. The greatest flooding hazard in this area is posed by the depth of water ponding on the surface, rather than the speed of the flood flows. It has been established that a 360 minute storm produces the worst-case flooding overall, with up to 0.9 m flood depth in urban areas and up to 1.2 m depth in open, undeveloped areas.

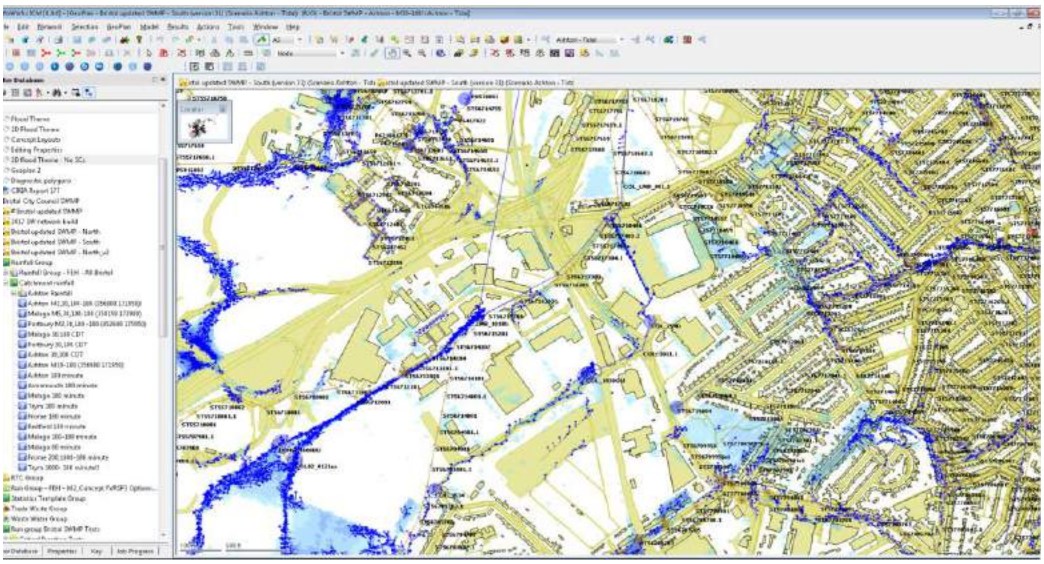


Figure 52: Flood predictions from 2D modelling (Ashton Gate area).

Model results can be viewed at a range of scales to allow area-wide and property-level impacts to be assessed, as shown in Figure 53 below.

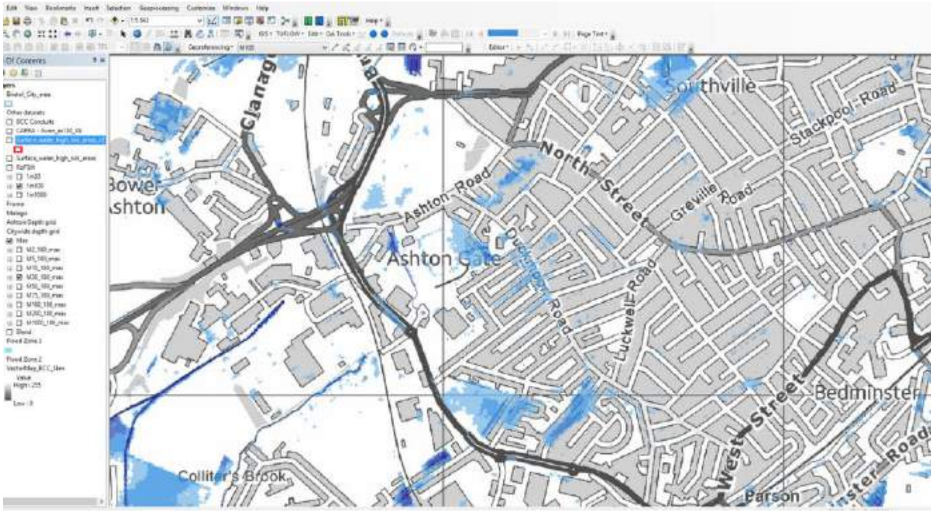


Figure 53: Flood predictions from 2D modelling (at overview / planning scale).

The key outputs include:

- A predictive model with City-wide coverage to inform:
    - The extent of flooding for a range of return periods
    - The depths of flooding for a range of return periods
    - The velocities of flooding for a range of return periods
    - Improved knowledge of the routing of flood water flow across urban surfaces
    - Areas at risk of ponding of flood flows
- Comprehensive knowledge of actual flooding incidents
- A model which identifies actual hydraulic deficiencies within the network

Hazard mapping also exists quantifying the effects of flood depths and velocities combined to assess the risk to human life. Figure 54 gives an example of this. Further explanation to the Defra Hazard rating methodology used is explained in the next model section.

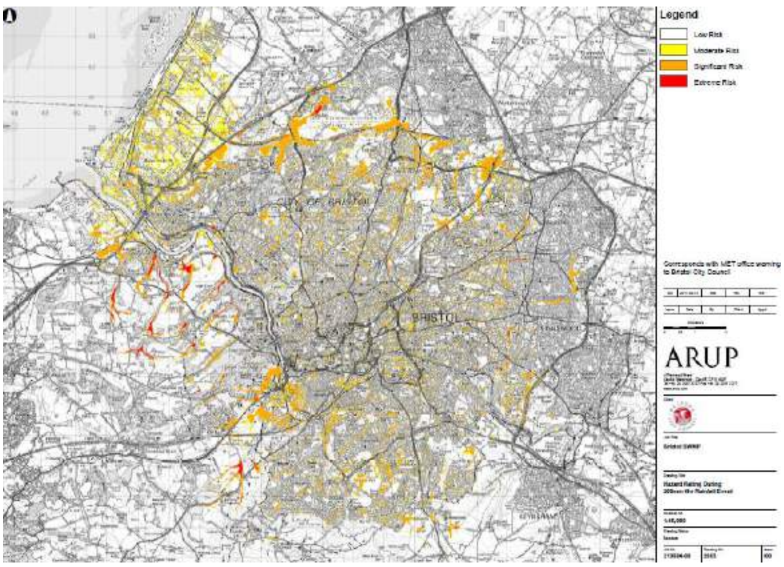


Figure 54: Surface water hazard mapping output.

Tidal and fluvial flooding model

The Central Area Flood Risk Assessment (CAFRA) model was composed to analyze the tidal and fluvial risk of flooding in the centre of Bristol. This area represents the main business hub of the city, amongst commercial, retail, social amenities and residential units. It is densely populated and the local and regional economy thrives from this area and its uses. The CAFRA model investigated a mixture of fluvial and tidal component combinations to assess the source of flooding that would pose the most significant risk. It is a computer software model of the tidal and fluvial systems in central Bristol, including assessment of joint probabilities of combined fluvial and tidal flows. The model was developed utilizing hydraulic and hydrological modelling. This comprised a 1D river network represented using ISIS software and 2D ground surface in TuFLOW software.

The standard of protection and operation of critical flood defenses and flood risk assets was also assessed through the project. This included those operating around the Floating Harbour and River Avon New Cut, at localities particularly susceptible to tidal flood risk.The Avonmouth Severnside Strategic Flood Risk Assessment has assessed the flood risk posed in another high risk region in the west of the city. The threat here again is from a combination of interconnected tidal and fluvial elements. Situated adjacent to the Severn Estuary, which boasts the second highest tidal range in the world, tidal flooding alone, is very apparent. The low lying areas in the Avonmouth region are also served with a series of drainage channel known as the Avonmouth rhine network. The interaction of these combined high tides and tide-locked outfalls makes for the requirement of a combined flood scenario assessment.

Tidal flood levels predicted for the Severn Estuary and tidal River Avon have provided some verification of the model outputs. This has enabled model calibration through the analysis high tides. A string of particularly high tides experienced in 2014 assisted with this. At a stage of the 19 year lunar orbit that resulted in exceptional astronomical tide levels. The equipment used to performe the checks are the Cumberland Basin, Bedminster Bridge and Avonmouth tide gauge. These tide gauges are radar sensor-type water level measurement gauges with telemetry. Values are provided in metres Above Ordnance Datum (AOD) level. The events in 2014 were in the region of a 1 in 10 annual chance event, meaning that the recorded levels have been used to validate and calibrate both the CAFRA and Avonmouth Severnside models in terms of in-channel water levels predicted by the models during lower return period events. There are no records of more extreme events meaning that calibration/validation of predicted flood extents is not possible. However, the recorded events have been used to calibrate hydrological rating curves to improve estimation of water levels during more extreme events.

As explained previously the Bristol central area is a thriving environment important to the livelihood of many Bristolians and also many from outside the area too. Its functioning is critical to the future longevity and prosperity of the city. Long term flood alleviation solutions are required but day to day operations and key services such as maintaining the highway network need attention due to their vulnerabilities to flooding. The Avonmouth area consists of a highly dangerous Control of Major Accidental Hazards COMAH site. Flooding of this could therefore cause problems of a great magnitude, hence the need for regulation of hazardous chemical substances and flammables used in the area. Also within the area is the Avonmouth

Sewage Treatment Works so there are critical services operating with the region that if affected could have severe consequences.

Hazard mapping exists for both the city centre and the Avonmouth area. An example of which is displayed below in Figure 55 and Figure 56. This is in accordance with the UK Defra standards. Determination of the hazard assessment criteria applied is defined in Figure 57.

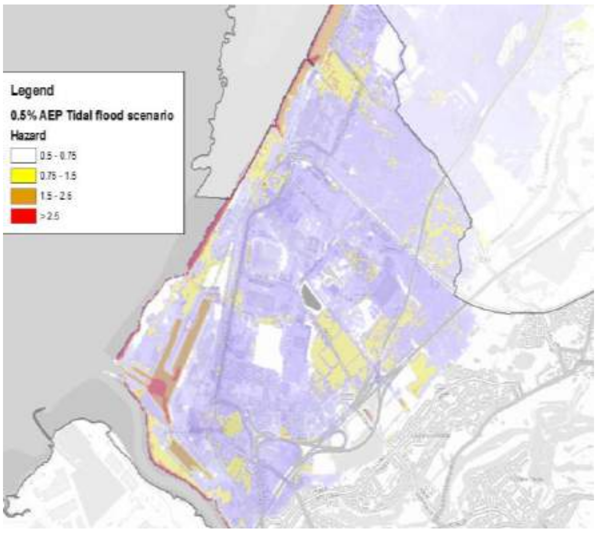


Figure 55: Avonmouth Flood Hazard Map.

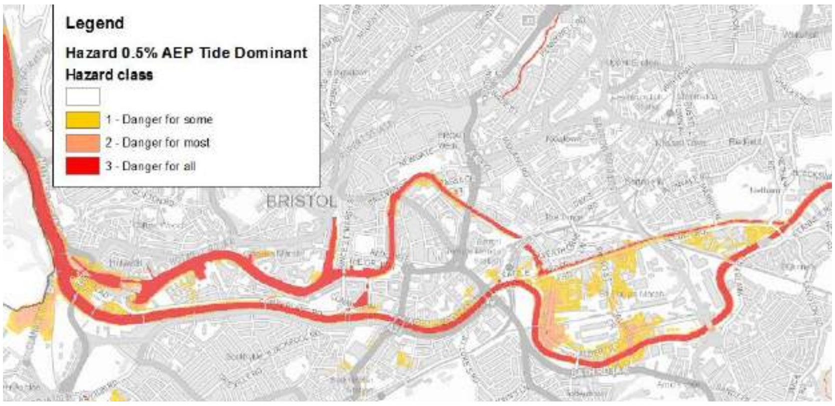


Figure 56: City Centre Flood Hazard Map.

d * (v+0.5) + DF

Velocity \ Depth	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
0.00	0.13	0.25	0.38	0.50	0.63	0.75	0.88	1.00	1.13	1.25
0.50	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
1.00	0.38	0.75	1.13	1.50	1.88	2.25	2.63	3.00	3.38	3.75
1.50	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00
2.00	0.63	1.25	1.88	2.50	3.13	3.75	4.38	5.00	5.63	6.25
2.50	0.75	1.50	2.25	3.00	3.75	4.50	5.25	6.00	6.75	7.50
3.00	0.88	1.75	2.63	3.50	4.38	5.25	6.13	7.00	7.88	8.75
3.50	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
4.00	1.13	2.25	3.38	4.50	5.63	6.75	7.88	9.00	10.13	11.25
4.50	1.25	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25	12.50
5.00	1.38	2.75	4.13	5.50	6.88	8.25	9.63	11.00	12.38	13.75

Categories of flood hazard:

	From	To	
Class 1	0.75	1.50	Danger for some
Class 2	1.50	2.50	Danger for most
Class 3	2.50	20.00	Danger for all

Note: The table gives values of flood hazard (= d*(v+0.5) +DF)

Figure 57: Defra Hazard rating.

Integrated flooding-traffic model

Traffic simulations and modelling within the Bristol research site will be carried out using the micro-scale traffic model utilising the SUMO software package (http://www.dlr.de/ts/en/desktopdefault.aspx/tabid-9883/16931_read-41000/). In contrast to Barcelona's meso-scale approach the micro-scale model simulates traffic at the individual vehicular level. Figure 58 shows a couple of screenshots showing the representation of the road network and traffic movements/representation within the SUMO model.

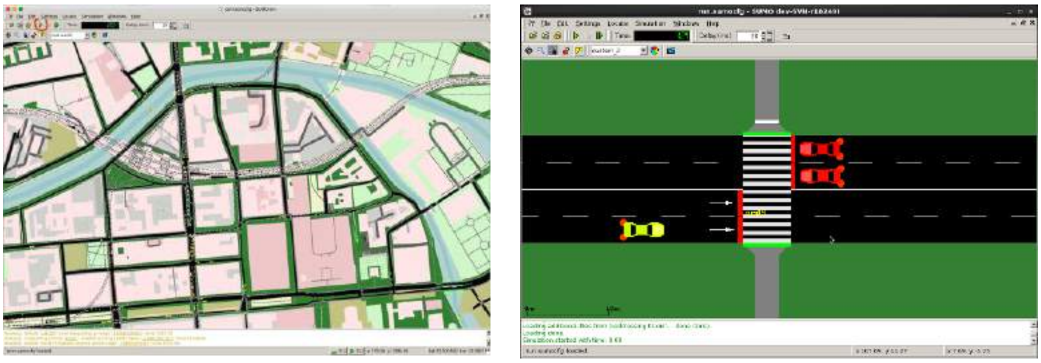


Figure 58: Screenshots showing traffic models within the SUMO GUI.

Like that of the Barcelona case study the roads/links within the SUMO model have properties that relate to the speeds at which vehicles can traverse them. Using the same GIS based approach as shown earlier in Figure 13 the effects of flooding on traffic within can be analysed to produce hazard inputs ready for impact analysis. In order to encapsulate the impacts of flooding at a spatial resolution suitable for micro-scale modelling the road network data needs to be broken up into link sections. Certain roads within OpenStreetMap data are represented as one continuous line feature with adjoining roads attached.

Whilst the data present for the junctions of the adjoining roads can be interpreted within SUMO the singular continuous representation of a road is not suitable for depicting localised impacts of flooding. For example if there was flooding present along road A located between the junctions of roads C and D (Figure 59) a singular based representation of the road would result in closing the entirety of road A thereby traffic along road A towards road D would not be able to reach roads B and C. If however roads are subdivided into links along their junction points (Figure 59-2) the flood water between junction of roads C and D (Road A_3) would not prevent flow of traffic along what was previously road A, to reach roads B and C.

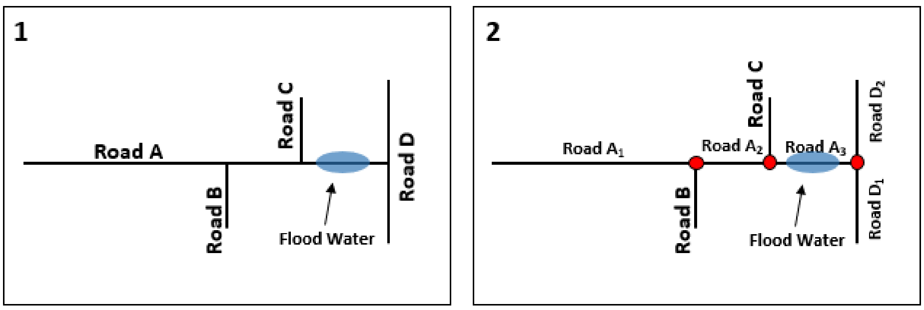


Figure 59: Visualising links in road.

For the city of Bristol the original road network OpenStreetMap dataset is represented by 21,246 line features. The “Feature to Line” tool in ArcMap® facilitates the conversion of the road network from that depicted in Figure 59-1 to Figure 59-2; post-conversion the Bristol road network now consists of 43,209 line features which is a 103% increase in features.

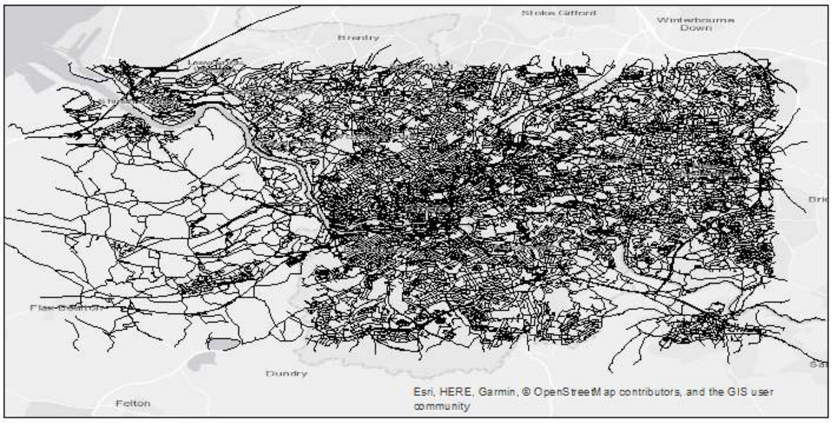


Figure 60: OpensStreetMap Road Network of Bristol.

In addition to the road network data, in order to run a micro-scale traffic model we need to determine/estimate the volume of traffic and routes taken by traffic within the network during normal running scenarios. For this an Origin-Destination matrix is required that provides details as to routes taken trough the city. For the Bristol case study this information exists in their existing macro-scale traffic model that utilises Saturn software (https://saturnsoftware2.co.uk/). Although information within this model is at a macro-scale, this information can be processed as a means to provide details as to traffic flows within the micro-scale model.

As highlighted earlier within Figure 13, a GIS based analysis is with respect to the flood model outputs and the road network to determine the status of the roads during an event. In the case of Bristol the flood model outputs provided in this analysis are in raster based format. In order to carry out an intersect analysis the raster data needs to be converted into polygons. This process requires more steps than its polygon based counterpart depicted in Figure 13, as shown in Figure 14.

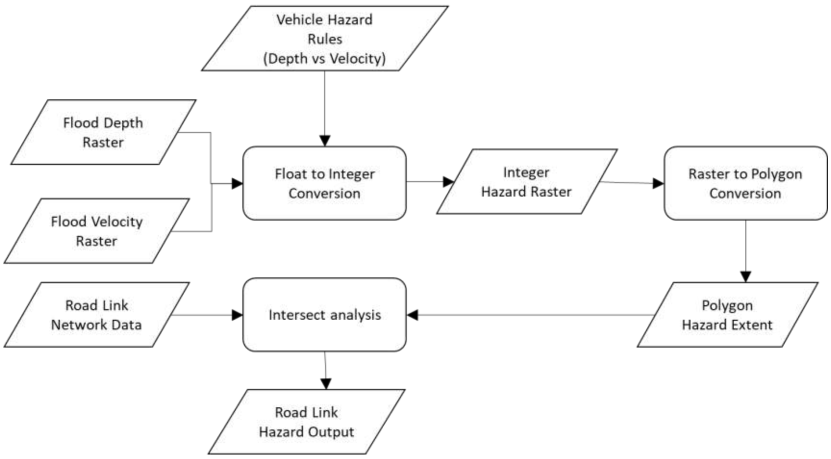


Figure 61: Process of generating hazard outputs with raster based flood data inputs.

The use of micro-scale modelling in the context of analysing flood impacts on traffic flows has already been successfully demonstrated in previous works within the PEARL project (Pyatkova K., 2015). The traffic modelling department in Bristol, however does not employ a micro-scale traffic model and currently uses the SCOOT (https://trlsoftware.co.uk/products/traffic_control/scoot) system for real-time traffic modelling and a macro-scale traffic model for simulations and analysis within the Saturn software package. A previous work (Apostolopoulos C., Bushell C., 2016) looked at the impacts of tidal flooding upon the transport network within the city of Bristol for a number of scenarios utilising the macro-scale traffic model (Saturn traffic model).

As part of the calibration and validation process for Bristol within RESCCUE, there will be three approaches used to validate and calibrate the effects of flooding upon traffic models:

1. Feedback from experts with the city's traffic modelling department
2. Cross-referencing historical events with model simulations
3. Comparative analysis of the SUMO micro-scale model against the Satrurn macro-scale traffic model

Within the city of Bristol they're looking into surface-water flooding as a result of both extreme rainfall events and tidal flooding. As such the hazards the events have upon road networks needs to be depicted utilising the spatial analysis approaches outlined in previous sections. Several hazard maps were produced as a result of analysing flood depths on road surfaces from surface-water flood model outputs for 1 in 30, 1 in 100, and 1 in 1000 year events. An example is shown in Figure 62, whereby the status of the roads is again determined by the parameters outlined earlier in Table 6. In contrast to the effects upon roads depicted in the Barcelona case study, the Bristol case study shows a greater number of links closed than reduced speeds for the 1 in 30 and 1 in 100 year return periods (Figure 63).

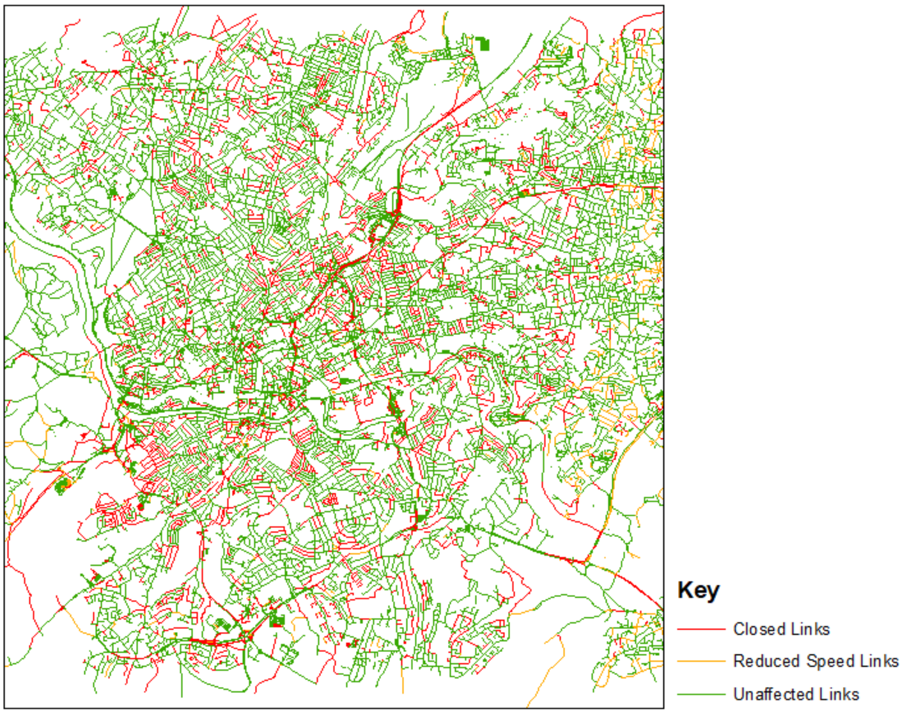


Figure 62: Impact of flooding on roads from rainfall with 1 in 100 year event.

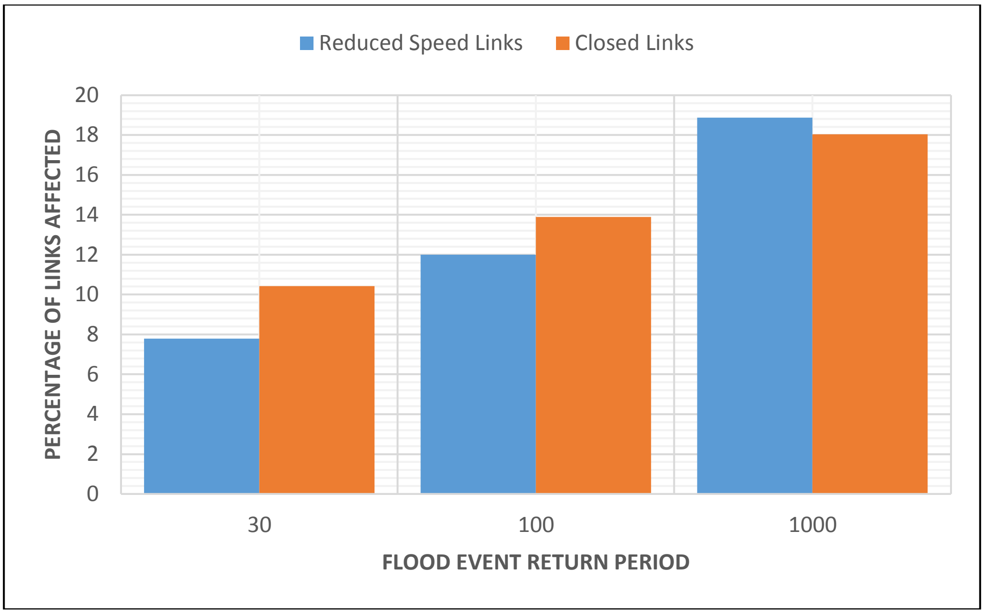


Figure 63: Percentage of road links affected that are located within the flood model domain.

For the Fluvial flooding the test analysis looks at a 1 in 100 AEP event both with and without flood mitigation strategies in place. Figure 64 shows the hazard maps produced for each scenario respectively. Although there is a significant reduction in the number of effected links, it is only through network analysis that considers the flow of traffic along both major and minor roads that a more complete view of the benefits of these mitigation measures can be assessed.

Utilizing the methodology shown here for the production of hazard inputs the effects of both pluvial and fluvial flood events will be modelled within the SUMO mico-scale model and the impacts upon the transportation network subsequently analysed (WP3, Task 3.4).

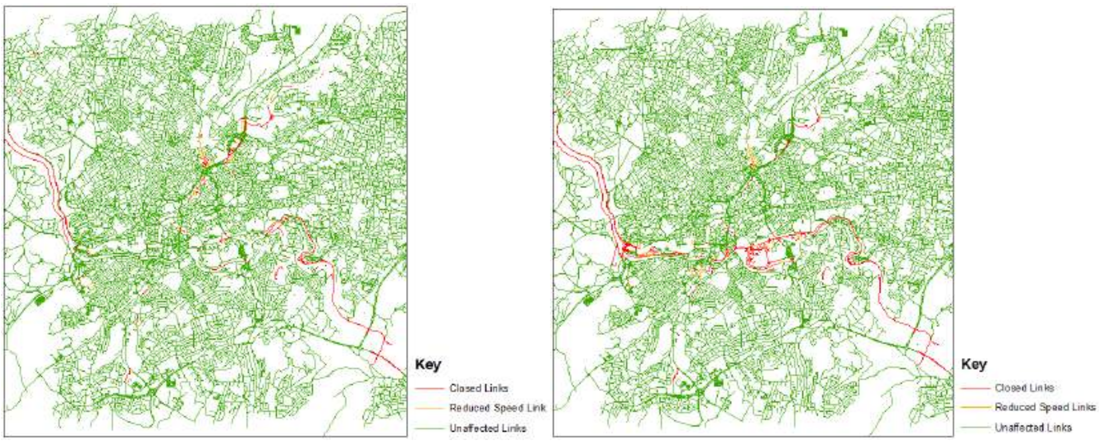


Figure 64: 1 in 100 AEP fluvial event with (on the left) and without (on the right) wall at upper end.

Conclusions of the Bristol case study

The case study of Bristol analyzed the impact of multi-hazards derived mainly form the water management sector like urban and coastal flooding. This chapter presented the so-called sectorial models used to simulate all the different hazards analyzed. Also, the results of the baseline scenario that corresponds to the actual situation are shown.

The 1D/2D urban flood model that was calibrated and validated based on real events observations, was used to simulate spatially distributed maps of maximum flood depths and velocities during design storms events of different return periods.

The outputs of the 1D/2D model are used to compute:

- Urban flood hazard maps for different return periods;
- Coastal and river flood hazard maps for different return periods;
- Maps of traffic interruption and traffic affections for different return periods;

These modeled hazards will be used to evaluate future scenarios and adaptation measures.

6. Multi-hazard assessment for the Lisbon Research Site

Lisbon city, the country's capital, covers an area of approximately 100 km^2, has a resident population of 547 733 inhabitants, but doubles with daily commuters. Located by Tagus river, has an extensive river front and a temperate climate, classified as Mediterranean, characterised by dry and hot summers and wet and fresh winter periods (for more information see RESCCUE Deliverable 2.1; Vela *et al*., 2017).

In Lisbon, relevant sectors considered include water supply, wastewater and stormwater, power supply, transports and waste collection. Water supply is not included within the scope of RESCCUE but climate change impacts are being addressed by the managing utility EPAL and impacts of drought has been studied in detail.

Services related to the **water cycle** include the Lisbon wastewater and stormwater systems both combined and separate sewers, around 1,400 km in total managed by the municipality (CML), with a variety of dimensions, materials and age. Furthermore, the sewer outlets of these systems are at the Tagus estuary and consequently performance depends on the river flows and sea level, the later depending on tides, storm surges and average sea level. Wastewater treatment is carried out at three main plants, managed by AdTA.

The sewer system is quite complex and largely combined but includes separate and partially separate sewers, dendritic and looped sewer networks. To face downstream conditions, such as tides and storm surges, several controllers are installed including weirs and tidal valves. Dry weather flows are diverted to the treatment systems, and weir levels allow excessive flows to flow to Tagus River to "relieve" the network and reduce flooding.

EDP Group is the largest energy producer, distributor and supplier of electricity in Portugal, manages the power supply in Lisbon.

In the distribution activity, the transported energy is channelled through the distribution grid. The distribution network allows the flow of energy to the supply points. Electricity distribution networks are composed of high, medium and low voltage lines and cables. Substations, processing stations and public lighting installations as well as the necessary connections to consumer installations and power stations are also an integral part of the distribution networks. EDP Distribuição manages the power supply in Lisbon.

The transport network in Lisbon includes structures as tunnels and viaducts in the road network. The city has a number of terminals and other interfaces that provide connections between several types of transportation, both public and private. The existing rail network is managed by several organizations: Infrastructures of Portugal S.A., Lisbon's Transports, Lisbon's Metropolitan (ML) and Carris. The municipality (CML) handles the collection and the transport of undifferentiated and recyclable waste manages waste services in Lisbon.

Sectorial models available for use in RESCCUE are listed in the following table. For the traffic sector and waste sector, models are not available for the city of Lisbon. A simplified approach is undertaken to allow estimating impacts on these infrastructures and associated services.

1D/2D Urban Drainage model

Lisbon drainage system is composed by three main subsystems: Alcântara, Chelas and Beirolas (Figure 65). Overall a total of 21 main catchments are considered within Lisbon although there are also four small catchments draining to neighbouring councils not considered in this study.

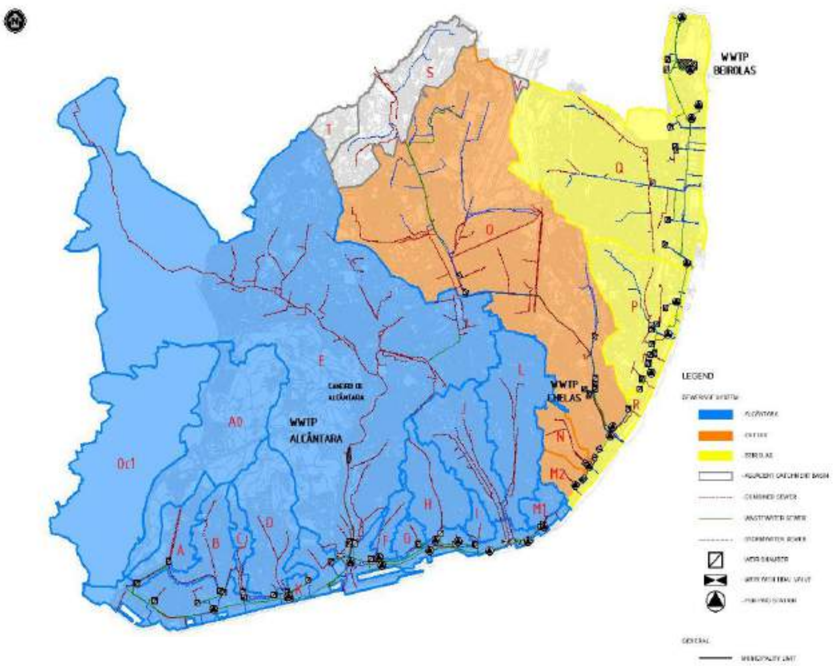


Figure 65: Lisbon's catchment basins and simplified drainage systems.

The modelling of the response to rainfall at Lisbon is based on a three-level approach using existing models of the drainage system, each with a distinct geographical scope, as follows:

1. **Lisbon Municipality citywide drainage system – 1D GIS based model**: main outputs are hydraulic capacity of the main sewer system network. Due to its simplified modelling process, the 1D GIS Tool is used to simulate the capacity of the drainage system facing wet weather flows.
2. **Alcântara drainage system – 1D Model SWMM**: main outputs include hydraulic behaviour of main sewers network and surcharge at main manholes. The 1D SWMM model allows assessing the performance of the drainage system facing different return periods and tide levels.
3. **Lisbon Downtown catchments J&L – 1D/2D SWMM and BASEMENT combined model**: main outputs include flooded areas, surface water levels and hydraulics in sewer network. The 1D/2D SWMM+BASEMENT model allows integrating the performance results of the drainage system facing different return periods and tide levels into the surface runoff modelling.

The objective of these models is to gain information about the occurrence of flooding in the city, for the current situation as well as for different scenarios of climate change. In Table 15, the main characteristics of the modelling approach at each level are presented.

Table 15: Drainage system main characteristics. (Hidra, Engridro, Bluefocus, 2015)

						Bulk System			
	Sub-catchments	Area (ha)	Inhabitants (2011)	Network	Diameter range (m)	Pumping stations	Weirs	Tidal valves	WWTP
City wide system	21	10,239	701,049	1430 km Mostly combined	0.4 – 1.2	23	63	5	Alcântara (750 000 p.e.) Chelas (225 000 p.e.) Beirolas (250 000 p.e.)
Alcântara system	15	6,473	464,515	310 km Mostly combined	0.4 – 0.6 Alcântara interceptor up to 8mx5.15m	11	28	5	Alcântara
Catchments J&L	2	597	72,225	133.5 km Combined	J: 1 - 2 L: 0.4 – 0.6	5	0	3	Alcântara

Legend: WWTP – Wastewater treatment plant; p.e. – population equivalent

Due to the complexity of Lisbon drainage system and limitation of available data, the modelling of the urban drainage system for the whole city is based on a conceptual modelling approach. This conceptual model was set for the municipal drainage plan development and updated with available information (Chiron, Engrido, Hidra, 2006).

Model inputs are dry and wet weather flows, associated to demographic and return period scenario being modelled. The results obtained are the flow rate, water depth and velocity for each sewer. The main inputs and outputs of the 1D GIS based tool are shown in Figure 66.

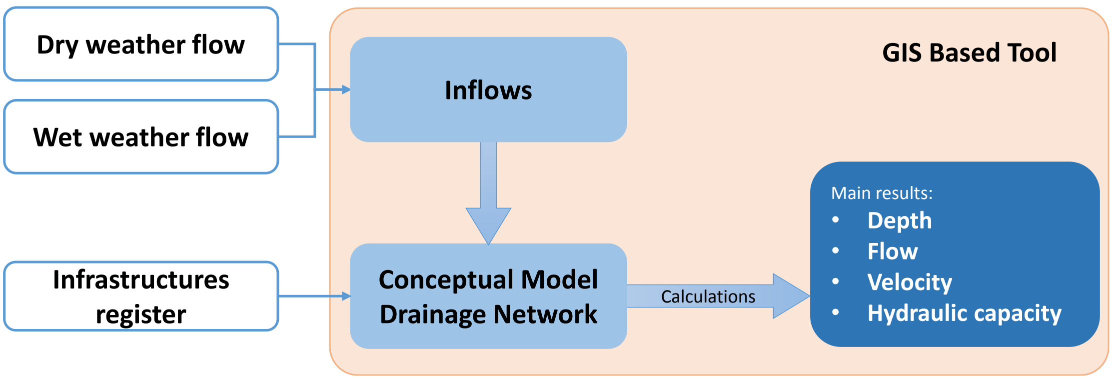


Figure 66: Main inputs and outputs diagram for 1D GIS based tool.

This model is defined by 421 sub-catchments, 797 junctions and 753 sewers, which make up a total of 173 km. From the 797 junctions, 218 are head junctions and 48 are final junctions, which discharge to a main trunk system, the Tagus River or to neighbouring councils. The results of this model are hydraulic variables, namely flow rates and velocities. The resulting citywide conceptual model is represented in Figure 67.

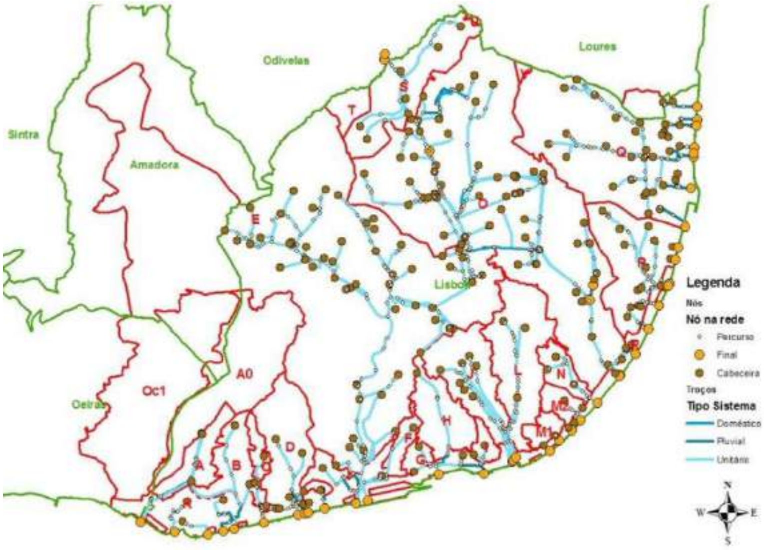


Figure 67: Citywide conceptual model for Lisbon drainage system and main catchments.

The Alcântara drainage system model was developed to support planning studies using SWMM (1D). It allows a physically based approach to this catchment even if using a simplified sewer system. This model accounts for 15 of the 21 Lisbon catchments, considering the main combined, domestic, and storm sewers.

The data on physical characteristics of the drainage system includes catchment basins, sewers, weirs, pumping stations and other equipment and its operation, and was provided by CML and AdTA, considering sewers with a diameter larger than 800 mm, both retail and bulk systems, including pumping stations, valves, outlets and the Alcântara WWTP. The model is more detailed in the downstream and in the downtown areas, which are critical areas especially prone to flooding. This model is composed by 95 sub-catchments, 1222 junction nodes, 28 outfalls, 98 storage nodes and 1238 links, from which 37 are pump links, 97 are orifice links, 62 are weir links, 16 are outlet links (corresponding to valves) and the remaining correspond to sewers, as represented in Figure 68.

Figure 68: Modelled Alcântara Drainage System (1D SWMM Model).

The main SWMM outputs that will be analysed herein, for distinct rainfall events with different return periods, are flow rates and velocities, water depth in the sewers and manholes' surcharges/flooding, although several other variables result from this simulation.

The prediction of flooding areas and water levels at the surface is a desirable development for Lisbon. Given the data limitations, a combined model SWMM + BASEMENT (VAW - ETH Zurich, 2017) was used for two of the most prone to flooding catchments of Lisbon, J and L. These catchments encompass historical and touristic downtown areas with several relevant infrastructures and services. These catchments are modelled using this approach due to its importance, potential high magnitude of social, political and economic consequences and the number of severe flooding events that have been occurring in the last years.

The use of 1D modelling tools enables the simulation of the drainage system infrastructures not allowing simulating the interaction with the surface hydraulic processes. For this reason, a 1D/2D model was considered in order to better assess the superficial hydraulic behaviour of overland flows. The model for this area includes 32 sub-catchments, 331 sewers and 318 nodes, from which six correspond to outfalls. Comparison of the model and the real drainage system is represented in Figure 69. The creation of the computational mesh (pre-processing) and the visualisation of the results (post-processing) are made in the open source QGIS software, with specific plugins, BASEmesh and Crayfish, respectively.

The SWMM simulation outputs are used as inputs in BASEMENT by selecting specific cells (corresponding to the drainage manholes) which will be sources of superficial runoff, and BASEMENT will allow to assess flow height, velocity and direction, and the flow rate at specific sections.

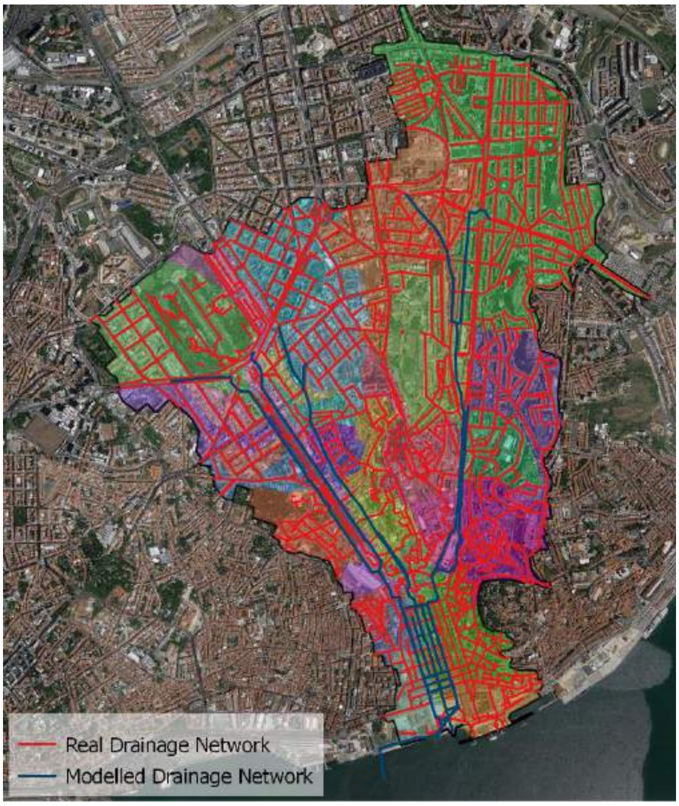


Figure 69: Real and Modelled Drainage Networks for J&L catchment.

Given data limitations for detailed hydrologic models, setting of conditions for modelling systems' response to recurrent events is carried out using Intensity-Duration-Frequency (IDF) curves.

The domestic flow is estimated from the resident population estimations and the water consumption per capita adopted in the Lisbon Water Supply Masterplan. The commercial and industrial activities and services flow is based on the 90,000 supply connections of EPAL, as well as part of the Loures and Amadora councils that also drain to this system. The infiltration flow is estimated as a percentage of the average flow of each sewer, which in the absence of accurate information about the condition state of the sewers is assumed as 50% of the dry weather flow.

The drainage system performance is strongly dependent on the tide level since it regulates the hydraulic capacity of the sewers under the influence of the tide. For Lisbon's tide gauge records (http://webpages.fc.ul.pt/~cmantunes/hidrografia/hidro_mares.html), and considering the variability of the tide level values, a maximum high storm tide level (MHSTL) of 2.27 m above the sea level was considered. Given the low probability of simultaneous occurrence of high storm tides and extreme rainfall events, a tide level of 6/7 of the MHSTL was assumed for current situation, resulting in a tide level of 1.95 m above the sea level. These values are in agreement with recent studies under the Municipal Strategy to Cope with Climate Changes (CML, 2016).

The three modelling levels are run for different return periods, being the simulation scenarios presented in Table 16.

Table 16: Simulation scenarios for Lisbon urban drainage models.

Scenario Code	Rainfall Event Return Period	Tide Level	1D GIS Tool	1D SWMM Model	1D/2D CMSB
CS-T02	T = 2 years	1.95 m	✓	✓	✓
CS-T10	T = 10 years		✓	✓	✓
CS-T20	T = 20 years		✓	✓	✓
CS-T50	T = 50 years		✓	✓	✓
CS-T100	T = 100 years		–	✓	✓

The models were calibrated and validated with available and reliable monitoring data (flow level and velocity measurements) in critical locations of the system.

Currently, there are 21 flow measurement locations operated by Águas do Tejo Atlântico (AdTA) which are considered relevant for monitoring the main drainage system of Lisbon. The equipment installed consists mainly of magnetic, ultrasonic and radar flow meters.

Besides using the reliable flow series from the monitoring stations abovementioned, the Alcântara drainage system model was also calibrated for specific rainfall events that occurred during September and October, 2014 and which resulted in serious flooding in Lisbon.

On the other hand, the water surface depth, resulting from the 1D/2D combined model, was calibrated and validated, taking into consideration the knowledge and records of and from more informal information in media reports.

The results of simulations for the current situation are presented for each level of modelling and for each scenario. From these results, the hazard flooding is mapped taking into consideration both simulation results and flooding mapping based on historical records namely the map included in the Municipal Master Plan. This approach provides an informed estimation of hazard mapping using the best information available.

For the whole Lisbon Municipality citywide drainage system (1D GIS based model), being a simplified model, the results obtained allow to have an overview about the system behaviour for the simulated scenarios, namely in relation to the main hydraulic characteristics when evaluating a drainage system, sewers' capacity and flow velocity.

The simulation results related to the hydraulic capacity of Lisbon's drainage system are presented in Figure 70.

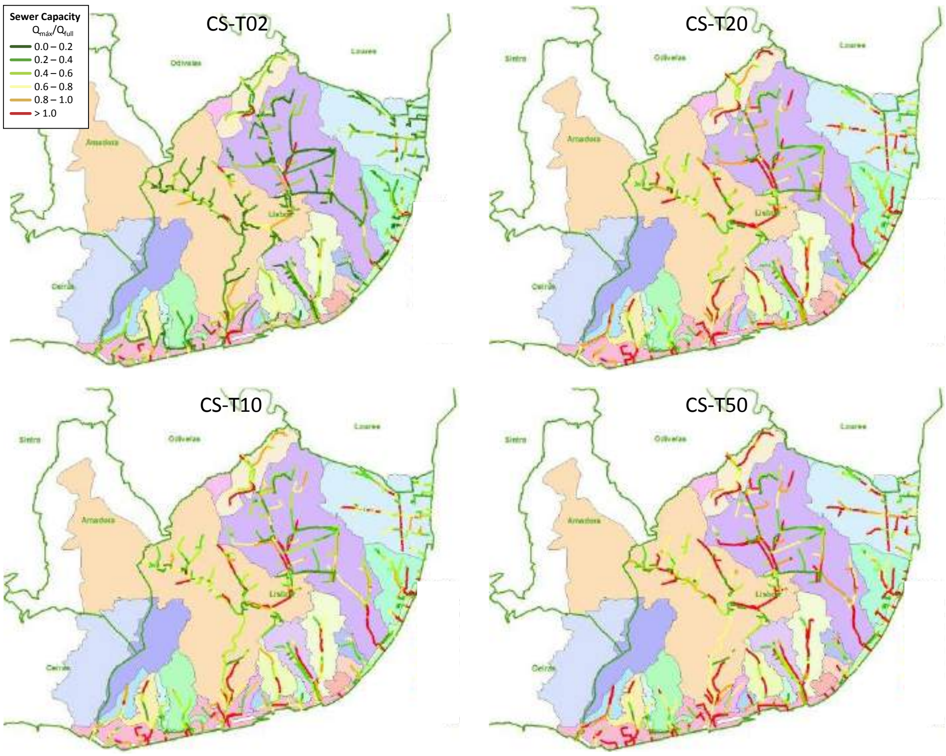


Figure 70: GIS Model results for Lisbon drainage system: sewer capacity (Q_{max}/Q_{full}).

For Alcântara drainage system – 1D SWMM model, the results from the dynamic 1D model are presented herein grouped as:

- Hydraulic capacity and overflow at flooded manholes
- Flow rate and velocity

The results presented herein, although considered more reliable, in particularly when compared with the citywide model, still derives from a simplified model. Nonetheless, this model helps understand the hydraulic and environmental performance of the main overall Alcântara system and reflects the performance at critical sections of the system, as already shown in several relevant plans and projects. The simulation results for sewers' hydraulic capacity of Caneiro de Alcântara (the main drainage infrastructure at Alcântara sewer system) are presented in Figure 71.

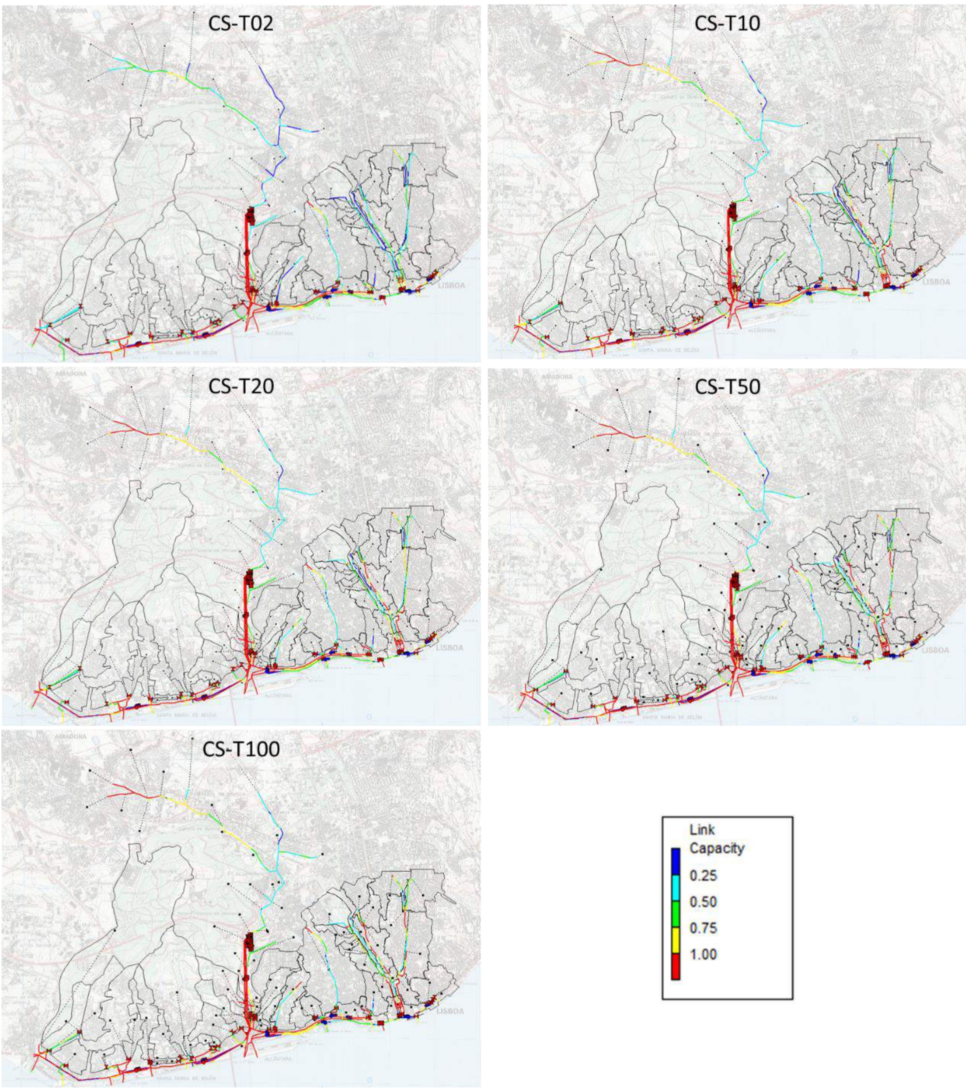


Figure 71: SWMM results for Alcântara drainage system – sewer capacity (L/s).

For the Lisbon downtown catchments J&L – 1D/2D SWMM and BASEMENT combined model, an overview of the results for the critical time (approximately 2:45 after the beginning of the rainfall event) and critical manholes locations, i.e. manholes that overflow, is presented in Figure 72. As expected, drainage performance tends worsen with increasing rainfall event return period, increasing consequently the flooded areas, surface water depth and manholes overflowing. As observed in Figure 73, the downtown area is very prone to flooding; therefore, the results for this area are presented in more detail.

From the results it is clear the effect of topography, which determines the overland flow direction and velocity, the main driver of the observed flooded areas, located at downstream flat zones. These are associated with the lack of capacity of the drainage system to accommodate the wet-weather flows, resulting in manholes' overflows that aggravate the flooded areas and surface water depth. The most critical flooding areas are located in Rossio, where surface water depth can reach up to 50-75 cm, even for rainfall events with a return period of 10 years.

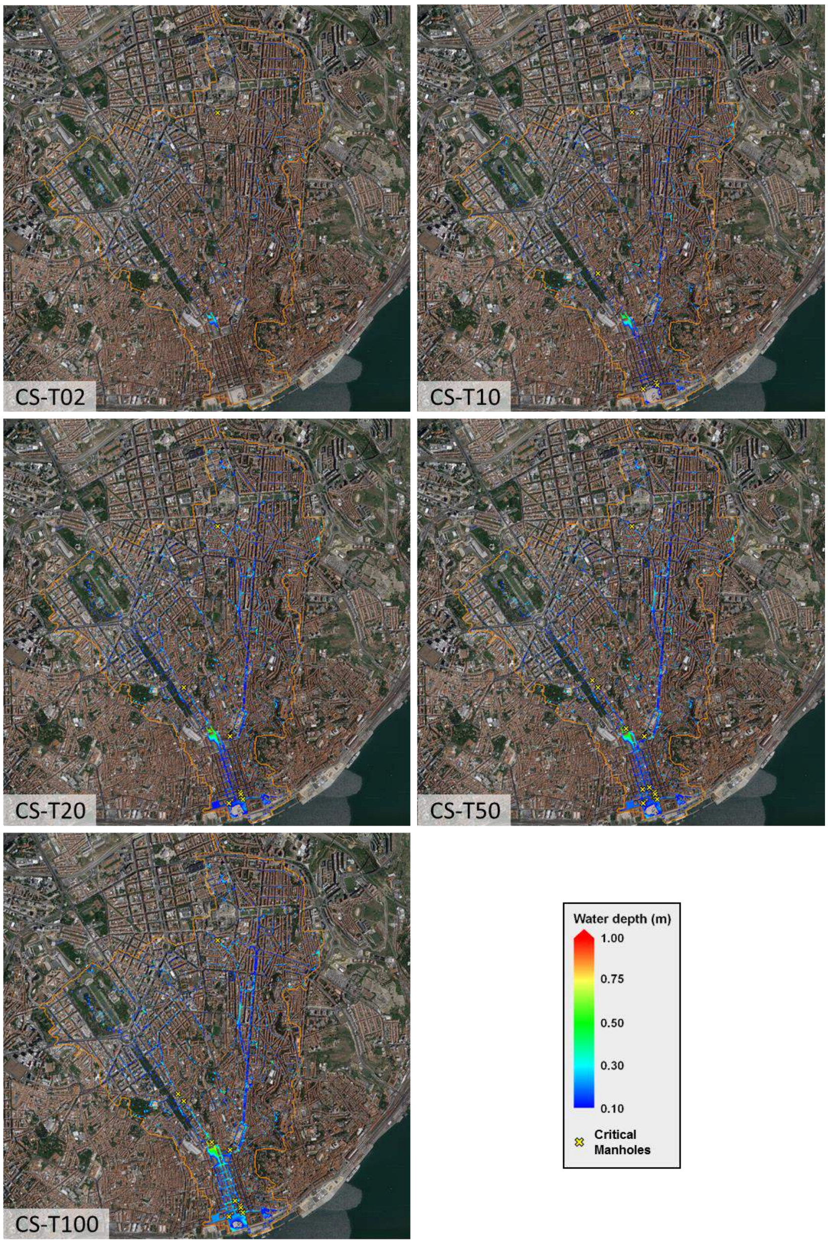


Figure 72: Overview of CMSB results and critical manholes location at critical time.

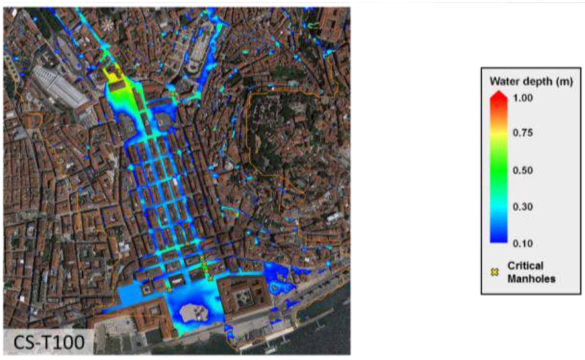


Figure 73: Example of CMSB results on Lisbon's downtown area at critical time for CS-T100.

Hazard maps for rainfall induced and tide induced flooding risks are presented in Figure 74 and Figure 75, respectively.

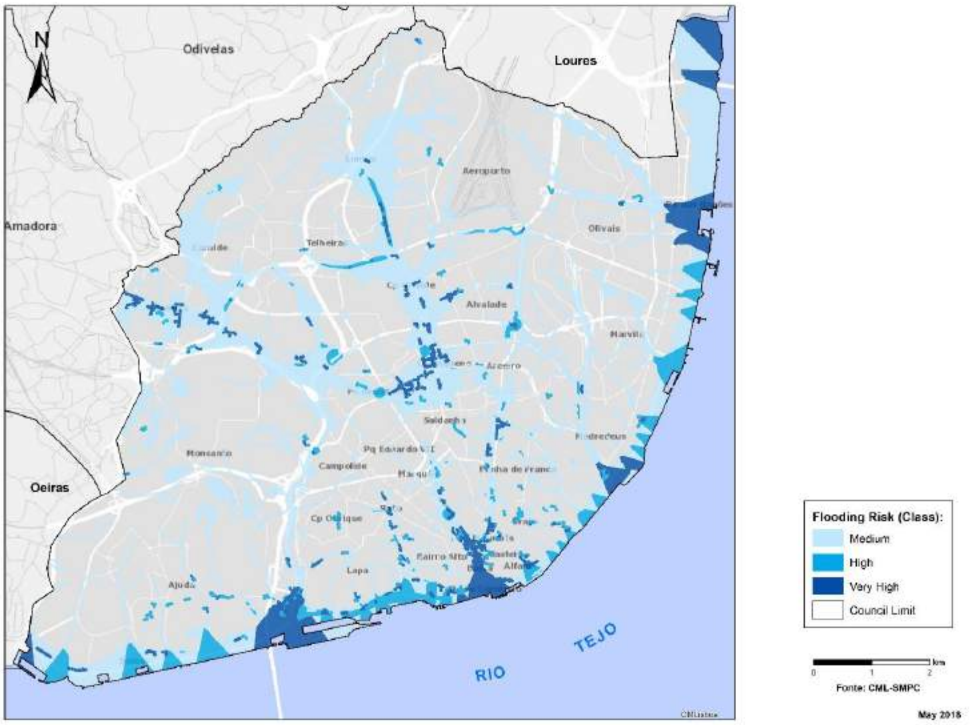


Figure 74: Rainfall induced hazard maps for Lisbon (current situation).

Figure 75: Estuary water level induced hazard maps for Lisbon (current situation).

Electrical model

The electrical model used in Lisbon research site is an EDP Distribuição internal software (Carvalho F. et al, 2017) based on technical and electric models, integrated with a geographic information system that can provide simulation of the electrical distribution network, with the identification of dependencies in case of failure.

Table 17: Electrical data Lisbon research site

Electrical infrastructure features	Data
Primary substations	27
Secondary substations	4.288
Number of clients	549.543
Quality of service zone	A
 Lisbon High and Medium Voltage Grid	 Lisbon Low Voltage Grid

The Distribution Planning System (DPlan) is a computer system for planning and operation of power distribution networks. This tool could simulate the possible impacts of climate change scenarios, related to water events. Considering the urban drainage modelling approaches, the DPlan allowed to identify which are the main effects in electricity supply and infrastructure in Lisbon and also how can electrical distribution sector respond and recovery from failures caused by water events. DPlan optimizes networks and integrates multiple functionalities (Carvalho F. et al, 2017):

- Analysis and optimization – with evaluation of system performance including investment analysis, reliability, quality of service, energy transit, short circuits. The analysis is instantaneous and occurs whenever some magnitude of the system is changed. Optimization is not instantaneous and needs to be requested. The analysis of the system is done in one window and the analysis of the ideal solution in another window. The analysis and optimization features integrated with the advanced interface features allow the user to make optimal planning;
- Manoeuvres restoration – for planning of unavailability, defect relief for service replacement, preparation of contingency plans and manoeuvre studies;
- Data processing – with advanced editing, selection, union, geographic visualization (including raster and vector maps), search;
- Communication – with client-server communication facilities, management of information update, export for verification, import of GIS data, and export and import in text format for communication with external applications.

As a planning system, DPlan supports the decision and proposes optimal investment and operating decisions, based on: best combinations according to the performance function specified by the user (or the company); because each individual decision was given by the user as possible. These decisions are investments, manoeuvres of reconfiguration, manoeuvres of rescue, replacement of cables and lines, etc. DPlan is able to select the optimal decisions for the user, to communicate them to other systems, and to document that selection.

DPlan is designed to provide easy and intuitive access to network data and results of analysis and optimization on distribution networks. The distribution system is a network composed of many nodes (hundreds, sometimes thousands) and an even larger number of branches, operating radialy. The network operates radially. The redundancy of branches is typically of 5% to 15% — 5% for large, widely spread networks with a strong rural component, 15% for smaller, urban networks. Redundancy serves as a reserve and for reliability purposes, allowing reconfiguration of the network. Most of the nodes of a distribution system correspond to delivery points or load points. Some nodes are injection points — distribution substations; some are switching stations and some others are simple connection points. Most of the branches correspond to electric cables, and other branches correspond to switching devices. Distribution planning (Carvalho et al., 1999) is to choose a new distribution system from a set of possible distribution systems to meet the expected load profile in a better way, more reliably and with fewer losses.

Based on flooding event and its 1D/2D Urban Drainage model approaches for Lisbon, DPLan provided simulations in power distribution grid to assess the impact in the electrical energy supply infrastructure, and test possible alternatives to recover the system and service. By combining the drainage models and the DPlan it was possible to identify the areas with the risk of flooding and which assets of the electrical infrastructure are potentially affected (Table 18).

Table 18: Urban Drainage model approaches and electrical infrastructure exposed.

Urban Drainage model	**Electrical Infrastructure (any component)**	
Lisbon municipality citywide drainage system main results concerning about the hydraulic capacity of the system	Primary substations Secondary substations Number of clients	23 3,122 364,354
Lisbon Council Sea Level Rise	Primary substations Secondary substations Number of clients	10 1,025 116,765
Lisbon downtown catchments J and L: main results concerning superficial runoff flooding areas	Primary substations Secondary substations Number of clients	13 2,070 231,480

Regarding the catchment basins J&L scenario, the DPlan simulation developed based in this model has few assumptions:

- The simulation was applied only to High and Medium voltage (HV/MV);
- By using the 1D/2D Urban Drainage Model it was possible to identify the electrical assets in flooded areas;
- Assessing those areas and searching the available historical data, it was identified the critical assets with flood risk that might be really affected: one primary substation and nine secondary substations;
- The identified assets are underground.

The simulation considered the critical assets affected by the scenario and developed the contingency plans per asset to optimize the recovery, based on the establish redundancy and the possible manoeuvres made by mobility teams. The available historical data indicate that only one primary substation was affected and became unavailable because of flooding at 31st of August and 2nd of October, both in 2003. In the Figure 76, water level reached is clearly visible on the walls of the substation.

Figure 76: Flood level registered in the walls of the flooded substation.

Regarding secondary substations, the historical data from 2010 describes that there were 3 assets stayed totally flooded (3 of 9 considerable risk of flooding) that were previously identified.

Figure 77: Flood level registered in secondary substations.

There are other several types of scenarios that can be also simulated:

- Dependency of the number of power transformer
- Failure of power transformer
- Failure of a single power transformer
- Failure of substation
- Failure of electric bus

Integrated flooding-traffic model

The approach to model the effect of flooding events on traffic in Lisbon takes advantage of the data available allowing the analysis of the whole city. Lisbon's smart control of traffic system monitors based on the Gertrude system is used for the control and real-time traffic management. Even if desirable, a more advanced system is not yet available. Therefore, data on traffic flows is limited and not sufficient to support a more detailed approach.

Given these limitations, the approach adopted is a GIS-based surrogate model making use of available information and results from flooding, thus allowing obtaining results to decision support on course of action to face expected effects of climate dynamics. Model is based in two types of data:

1. Rainfall induced flooding hazard maps and coastal overtopping flooding hazard maps for each considered scenario. The hazards maps take into account modelling results as well as historical data on flooding characteristics and effects;
2. Data to establish exposure and vulnerability of traffic infrastructures.

As for the surrogate model to estimate impacts on global city traffic, infrastructures and users three main steps are carried out:

- mapping of hazards (rainfall induced and coastal overtopping flooding);
- mapping of infrastructures (roads, interfaces, critical components), classified according to functional importance;
- spatial exposure and criticality analysis.

Main outcomes are urban areas exposure and transport sector critical components for each scenario analysed and estimation of broad impacts on the service. Information from historical events is taken into account to complement the hazard maps, namely with regard to range of water levels expected in different locations. Results from analysis of historical flooding data, meteorological data, estuary level data and modelling outcomes allowed to obtain a cross validated mapping of this hazards.

Lisbon municipality road network hierarchical classification, based on attributes of roads has four levels, according to Lisbon Master Plan, comprises the following levels:

- 1st level - Structuring network - ensures inter-county connections and crossing of the municipality as well as the most extensive trips within the city of Lisbon;
- 2nd level - Main distribution network - ensures the distribution of the largest flows of traffic to the municipality, as well as the average routes and access to the structuring network;
- 3rd level - Secondary distribution network - is composed of internal routes and ensures the distribution of proximity, as well as the referral of traffic flows to the upper level;
- 4th level - Local distribution network (neighbourhood network) - is composed of structural routes at the level of the neighbourhood, with some capacity of outflow, but where the pawn has greater importance;
- 5th level - Local access network (neighbourhood network) - guarantees road access to the building, and must meet privileged conditions for pedestrian circulation.

Regarding critical components for functioning of road network, relevant tunnels and level crossings are identified. The maps for the classified road network and critical components is shown in Figure 78, where level 4 and 5 are aggregated. In terms of traffic, daily commuters determine the traffic volume. Despite the limited data, an overview of the overall flows (annual daily average) illustrates critical locations at city boundaries (Figure 79). For the purpose of this project, also rail network in Lisbon was identified (Figure 78). In **¡Error! No se ncuentra el origen de la referencia.** the underground network is mapped.

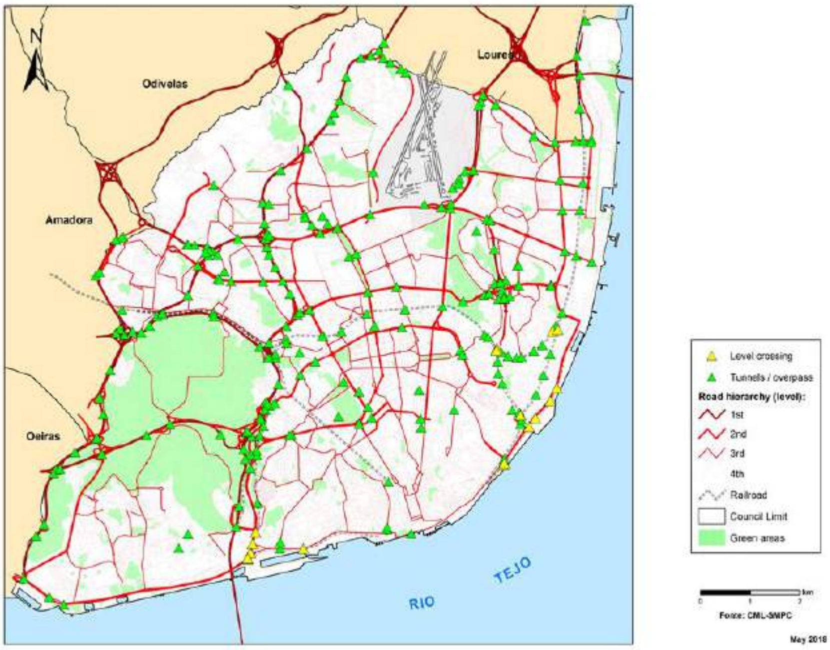


Figure 78: Road network and critical components (level crossings and tunnels) mapping in Lisbon.

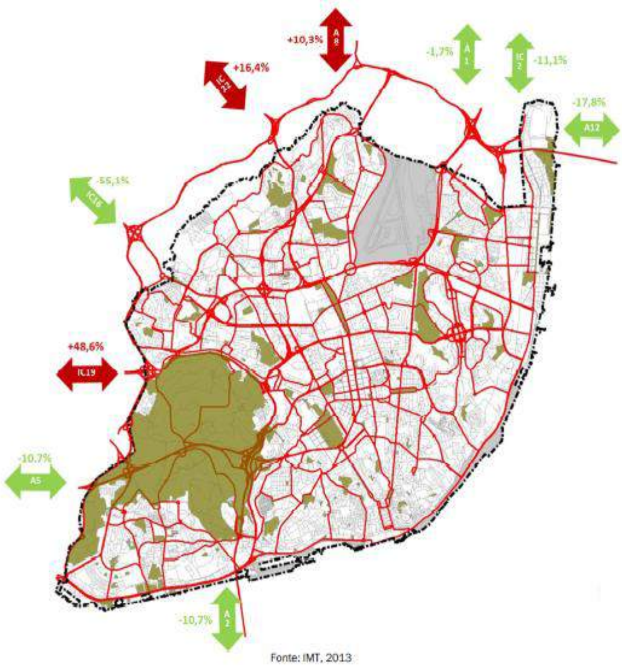


Figure 79: Daily traffic at Lisbon municipality boundaries.

Transport users interfaces, including docks and underground stations, are considered critical for city resilience to climate related hazards. These include any location where users commute from a type of transport (public or private, including parking facilities) to another within Lisbon municipality boundaries. Interfaces are classified as function of type, volume and supply of transports, as well as number of passengers.

Calibration and validation of this surrogate model approach was carried out by cross-checking results with past events recorded information. This was undertaken especially for critical or severe historical occurrences.

The exposure of transports infrastructures and services for different levels of hazards is presented in Figure 80. The vulnerability is assessed using as criteria the hierarchical classification of the roads and interfaces. Results for the selected metrics are in Table 19he results allow evaluation of exposure of transports infrastructures and services for different levels of hazards. The vulnerability can be evaluated from the hierarchical classification of the roads and interfaces.

Globally, rail network has higher values of exposure to flooding hazard than road network since a railway follows the coast within the area exposed to flooding due to river overtopping. Although these results already provide an indication, specific risk factors need to be analysed for a more detailed identification of most vulnerable zones. Taking into consideration the whole road network, the less important roads in terms of traffic are more exposed to flooding 4th /5th level: 33% are exposed to moderate to very high rainfall induced flooding and globally 41% of road length are exposed. Road network (5.31%) is globally less exposed then rail (27%) to tide induced flooding

Table 19: Road and rail networks exposure and vulnerability metrics to flooding hazards.

Network type/classes		Length affected by rain induced flooding				Length affected by tide induced flooding
	Length (km)	Flooding risk class ->	Moderate	High	Very high	
Road 1st level	88.9	% total	1.47	0.11	0.17	0.07
		% 1st level	25.14	1.93	2.91	1.27
Road 2nd level	175.0	% total	3.65	0.82	0.71	0.38
		% 2st level	31.72	7.09	6.21	3.50
Road 3rd level	174.5	% total	3.11	0.78	1.00	0.67
		% 3st level	27.00	6.74	8.71	6.08
Road 4th / 5th level	1153.3	% total	17.18	3.86	4.04	4.18
		% 4st level	22.64	5.09	5.33	5.77
ROAD TOTAL	1519.7	% total	23.94	5.56	5.93	5.31
RAIL TOTAL	34.36	% total	50	19	12	27

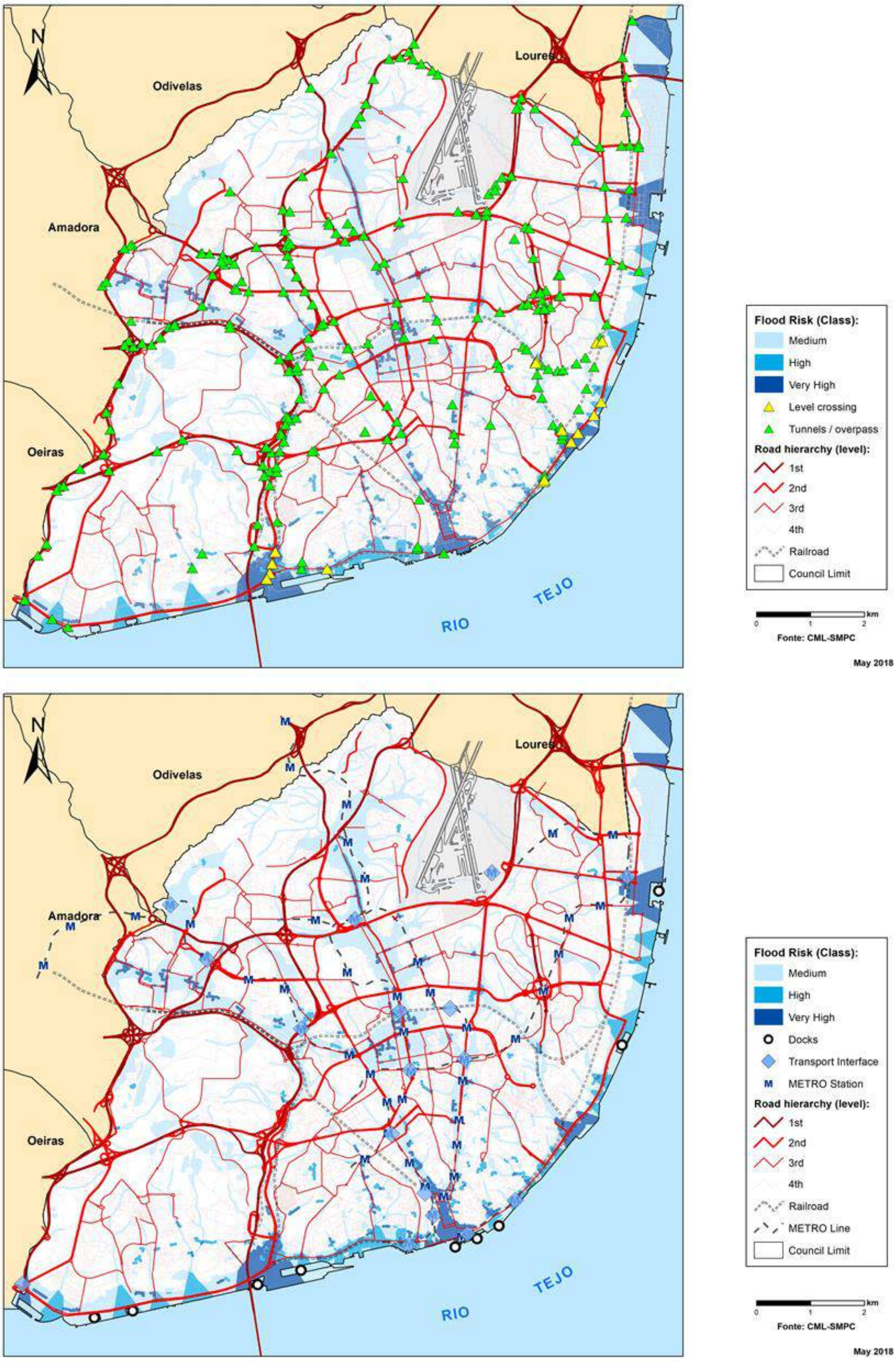


Figure 80: Results for exposure and vulnerability to rainfall induced flooding: mapping for transport networks and interfaces.

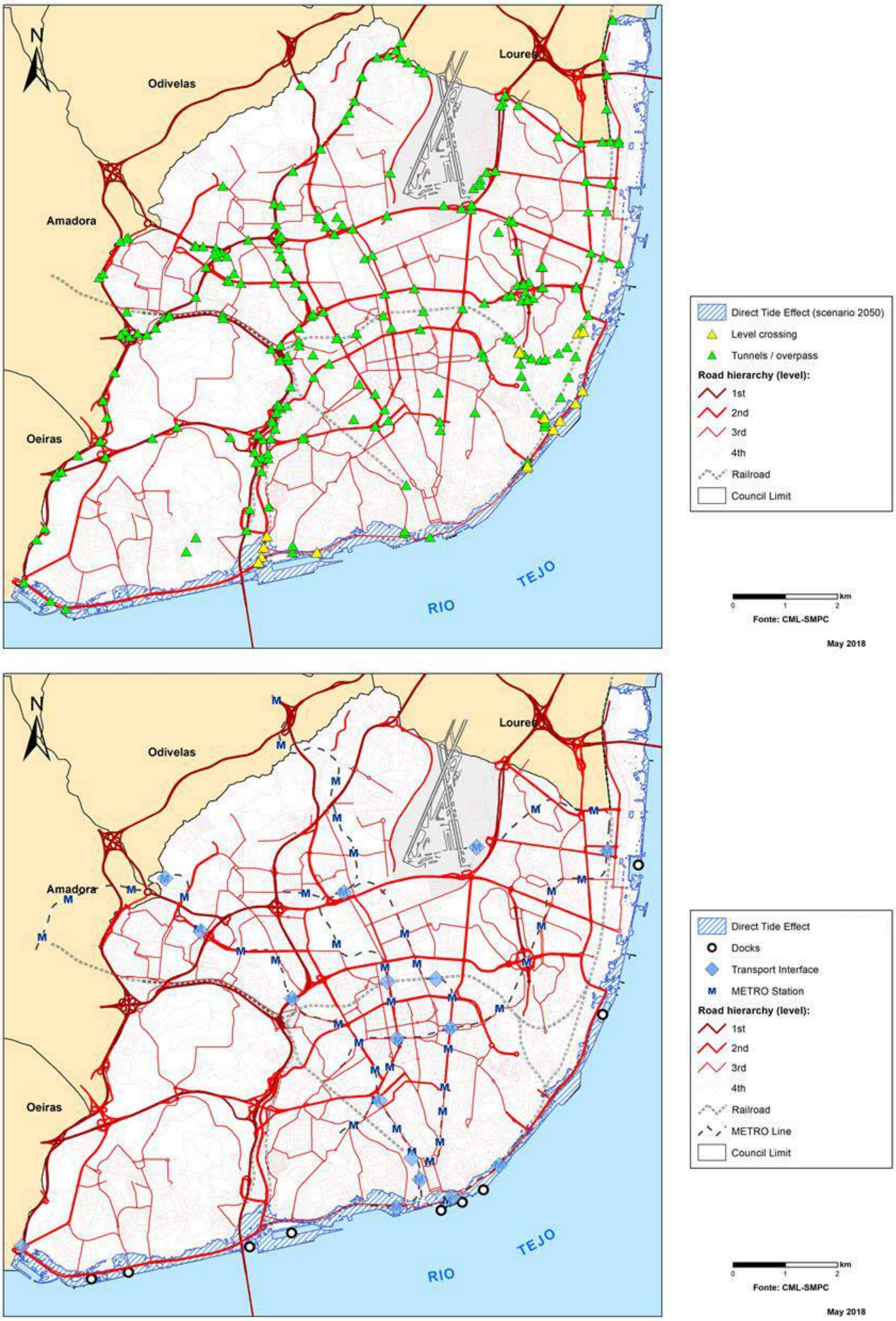


Figure 81: Results for exposure and vulnerability to estuary level induced flooding: mapping for transport networks and interfaces.

Integrated flooding - wastes management model

The approach to model the effect of flooding events on wastes management in Lisbon takes into consideration the effects recognised as disruptive to the city and the data available. The effects from the failure of the drainage system causes disruptions on waste collection components including containers overturn, dragging, floating, filled with water and damage. Additionally, this kind of failure can also cause delays on the collection service but this is considered as a disruption derived from impacts on the transport infrastructure. Overland flows can result in spillage of wastes, in spread of wastes on streets, blockages of inlets and other drainage components. Accumulation of debris on streets requiring deep cleaning before resuming service. Since use of mechanism to avoid movement of containers is almost generalised, these problems are limited today.

Therefore, the approach adopted herein is to take into consideration the different systems for waste collection in the whole city and analyse the exposure and the vulnerability to flooding taking into account the solutions in place in the different areas.

i. Lisbon has different solutions for urban wastes collection. The main collection systems are: large public containers (bring banks) – several containers for different types of wastes;
ii. door-to-door (PaP) – inside buildings, bins or bags, outdoor only at specific hours in specific days;
iii. pneumatic (pneumática) - network of underground vacuum conduits to collect wastes. Only in one area of Lisbon, Parque das Nações;
iv. self-delivered (centros de receção de resíduos).

Waste are collected by type in dedicated containers: mixed wastes, glass, paper, packages, biodegradable, batteries, oils. Other wastes such as bulky waste, furniture, garden wastes, construction and demolition wastes, electrical and electronic equipment are collected on demand directly by truck. In the collection, solutions use bags, bins and containers, with different sizes and colours. The area of Lisbon in roughly divided in two parts where collection in the door-to-door system are alternating. For all solutions, there are vehicle routes established to transport the wastes to further processing.The containers in use today are already significantly resistant to flooding. In Table 20, typical containers used for each zone type are described. Exposure and vulnerability to the effects of flooding is widely minimised with the type of solutions utilised.

The approach adopted follows the one used for traffic and transport infrastructures, a GIS-based surrogate model making use of available information and results from flooding, thus allowing obtaining results to decision support on course of action to face expected effects of climate dynamics.

For wastes, model is based in two types of data:

1. Rainfall induced flooding hazard maps and coastal overtopping flooding hazard maps for each scenario considered. The hazards maps take into account modelling results as well as historical data on flooding characteristics and effects;
2. Data to establish exposure and vulnerability of wastes components. Impact on collection circuits is considered within the previous section but planning of circuits allows flexibility in adaptation to the specific circumstances.

Table 20: Types of wastes collection systems: containers used typically.

"Ecoponto": ▪ street bring bank for selective wastes ▪ Door to door to mixed wastes	 **Glass, paper, packages, batteries**	 **Mixed wastes**
"Ecoilhas": ▪ street bring bank for selective wastes ▪ Door to door to mixed wastes	 **Glass, paper, packages, batteries**	 with support (not shown in photo) **Mixed wastes**
"PaP": ▪ Door to door for selective wastes and mixed wastes except glass (bins kept indoor except at collection days and time)	 **Mixed wastes, paper, packages**	 **Glass**

As for the surrogate model to estimate impacts on global wastes, 3 main steps are carried out:

- mapping of hazards (rainfall induced and coastal overtopping flooding);
- mapping of zones and containers location;
- spatial exposure and criticality analysis.

Results from analysis of historical flooding data, meteorological data, estuary level data and modelling outcomes allowed to obtain a cross validated mapping of this hazards. Critical components are those containers that are not yet restrained with a support to restrict movement. These remaining situations are in limited numbers and not localised by a specific criteria. Therefore, a criterion for improving systems resilience is to upgrade those components which are localised in areas more exposed to flooding from the results of this surrogate model approach.

Validation of this surrogate model approach was carried out by crosschecking results with past events recorded information. This was undertaken especially for critical or severe historical occurrences.

The exposure of wastes infrastructures and services for different levels of hazards is presented in Figure 82 and Figure 83. Results for the selected metrics are in Table 21. The results allow evaluation of exposure of wastes infrastructures and services for different levels of hazards.

Globally, in Lisbon, there are 55237 collection locations and 204004 containers. From these results, only 20% of the locations and 22% of containers are exposed to flooding. The "door-to-door" system comprehends a large number of locations and containers, respectively, 64% and 82% of total installed. However, globally, only around 20% are exposed areas. Furthermore, vulnerability is low since the time the containers are outdoor is reduced to few hours per week, depending on type of waste. A significant number of the containers exposed has a locking system, which limits the movement of the containers, adding to the stability of these components when subject to flooding or overland flow. These results are of use for defining the strategies in terms of upgrading of the system with stabilisation or restraining mechanisms, as well as option for underground alternatives.

Table 21: Wastes components exposure metrics to flooding hazards.

Type		Length affected by rain induced flooding				Length affected by tide induced flooding
	Total n. locations / n. bins	Flooding risk class ->	Moderate	High	Very high	
"Eco ilha"	3335 4367	n. location n. bins	603 808	80 100	34 39	45 64
		% location % bins	18 19	2 2	1 1	1 1
"Eco ilha" Underground	107 120	n. location n. bins	44 49	0 0	13 16	13 16
		% location % bins	41 41	0 0	12 13	12 13
"Ecoponto" Aboveground	1358 1408	n. location n. bins	234 242	54 70	175 192	161 187
		% location % bins	**17** **17**	**4** **5**	**13** **14**	**12** **13**
"Ecoponto" Underground	37	n.	3	5	7	0
		%	8	14	19	0
Paper reception centre	87 297	n. location n. bins	3 4	35 90	0 0	7 10
		% location % bins	3 1	40 30	0 0	8 3
Street bring banks (90 to 1100 L)	165 295	n. location n. bins	**34** **64**	**12** **31**	2 3	7 **23**
		% location % bins	21 22	7 11	1 1	4 8
Door to door	35321 168019	n. location n. bins	6760 34973	1406 6681	3017 11761	608 2225
		% location % bins	**19** **21**	4 4	9 7	2 1
Glass Aboveground	2364 2402	n. location n. bins	629 635	161 161	174 178	47 47
		% location % bins	**27** **26**	7 7	7 7	2 2
Glass Underground	26 30	n. location n. bins	7 7	0 0	2 6	2 6
		% location % bins	27 23	0 0	8 20	8 20
TOTAL LOCATIONS	**55238**	**n.** **%**	11208 **20**	2343 **4**	5275 **10**	1533 **3**
TOTAL BINS	**204004**	**n.** **%**	45508 **22**	8583 **4**	15579 **8**	3033 **2**

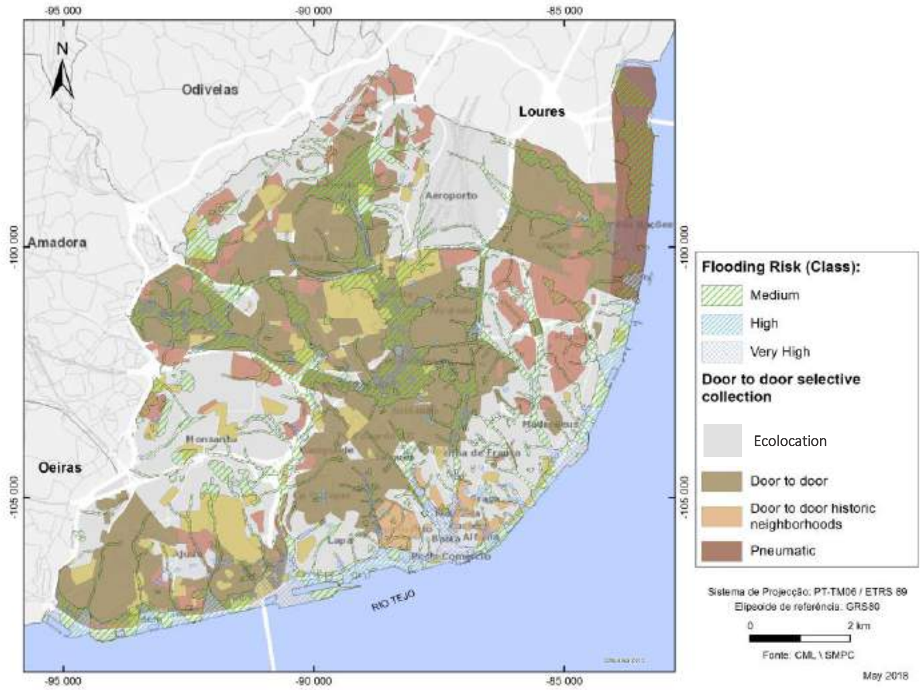


Figure 82: Results for exposure related to rainfall induced flooding: exposure - hazard mapping for wastes collection system.

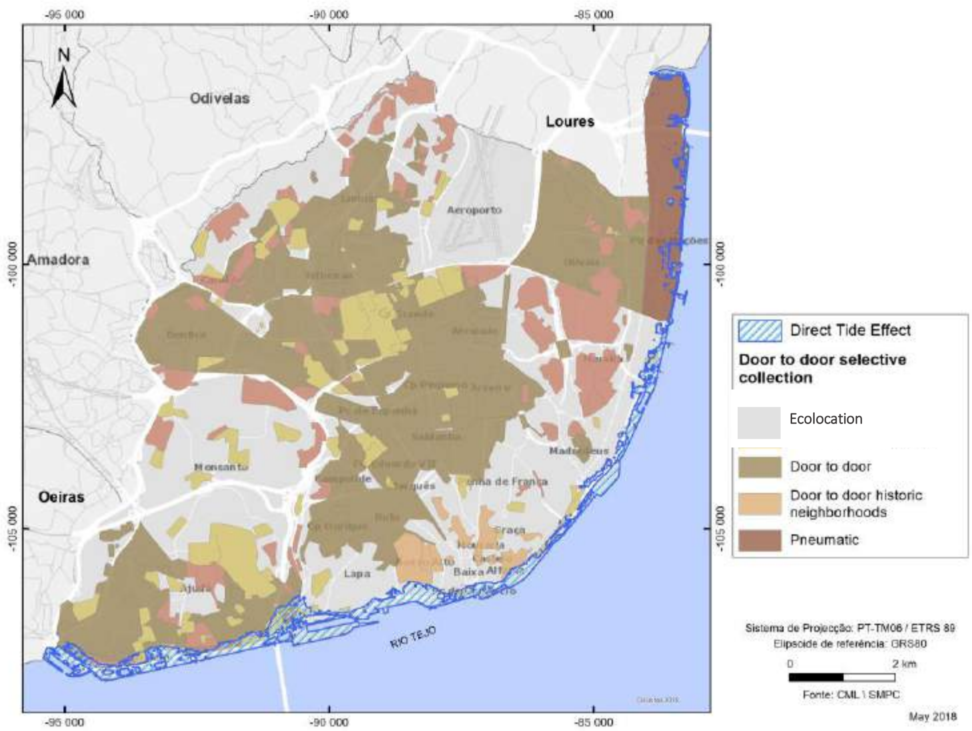


Figure 83: Results for exposure related to estuary level induced flooding: exposure - hazard mapping for wastes collection system.

Conclusions of the Lisbon case study

The case study of Lisbon analyzed the impact of multi-hazards derived mainly form the water management sector like urban flooding. This chapter presented the so-called sectorial models used to simulate all the different hazards analyzed. Also, the results of the baseline scenario that corresponds to the actual situation are shown.

The 1D/2D urban flood model that was calibrated and validated based on real events observations, was used to simulate spatially distributed maps of maximum flood depths and velocities during design storms events of different return periods.

The outputs of the 1D/2D model are used to compute:

- Urban flood dazard maps for different rainfall return periods;
- Maps of traffic interruption and traffic affections for different return periods;
- Maps of electrical infrastructure affected for different return periods;
- Maps of flood affected waste management sector for different return periods;

These modeled hazards will be used to evaluate future scenarios and adaptation measures.

7. Discussion

New methodologies based on integrated models were used to quantify hazards for urban services operation for the actual situation. The outputs of the hazard assessment will be used in other parts/tasks of the project for risk assessment (WP3) and also for an urban resilience analysis (WP4) that will analyze in a holistic city perspective the cascade effects of the different hazards quantified here.

Urban flood is considered as a major hazard for the three cities of Barcelona, Bristol and Lisbon and it was quantified in a similar way for the three cases: by setting up an urban drainage model to simulate both the urban drainage network and surface flooding (1D/2D models). The three cities are affected by pluvial flooding due to limited urban drainage infrastructure capacity. Barcelona is also affected by coastal flooding due to for instance sea level rise and storm surges; Lisbon by estuarine flooding due to the interaction between the river and the sea and Bristol by fluvial and tidal flooding.

Urban floods generate several hazards, like to pedestrians, road traffic, electrical stations, etc. In some cases, flood hazards are calculated by applying specific hazard criteria for urban areas. For instance, high hazard for pedestrians results from selected criteria that combine flood depth and water velocities that produce pedestrian instability in flood waters; similarly, high hazard for the road traffic can result from selected criteria of flood water depth that would cause traffic disruption. In other cases, flood hazard is calculated using the so-called sectorial models that integrate flood with the electric and traffic sectorial models. The flood hazards and the flood derived hazards for the electric and the traffic sectors are calculated in a similar way in all the three cities are. While the electric and traffic models of Barcelona and Lisbon are based on simple GIS (Geographic Information System) based analysis, the models of Bristol are more advanced with spatially and temporally outputs.

Barcelona and Lisbon also quantified flood hazards for waste collection containers. This hazards were computed by applying waste container stability criteria to flood simulation results.

There are also many hazards that are not derived from urban flooding and that were calculated and presented in the following.

The case studies of Barcelona and Bristol quantified the hazards of combined sewer overflows. Bristol used an urban drainage model to compute the number and volume of combined sewer overflows (CSOs) and defined hazard levels as a function of such variables. Urban drainage models for CSO simulations are similar to flood models in terms of data requirements, while the model setup can be simpler (the simulation of 2D flooding can be omitted). Barcelona used a coupled urban drainage and sea water quality model to compute sea water bacterial concentrations from CSOs and defined hazards for people bathing based on these concentrations.

The case study of Barcelona also quantified the hazards due to sea level rise on coastal infrastructure; the future drought hazard for water resources availability and the impacts of river turbidity for drinking water supply. The drought and river turbidity are hydrological / water resources models that require water level measures in hydrometric river stations and reservoirs, turbidity measurements in the river, hydrological data to characterize hydrological losses, evapotranspiration dada, exploitation rules of the reservoirs, etc.

Overall, this model based framework that was tested for three different cities can be considered generally applicable to other cities. The models and the observation data needed for this methodology are also generally available through the internet and by the different municipalities or sectorial utility companies (water, electrical, traffic, etc.).

The computational time of the models, particularly the 2D flood models and the 3D sea water quality models, is significant. For instance, a simulation of a 3-4 hours flood event from design storms can take in the range of 6 to 24 hours mainly depending on the available computational capacity. Moreover, a 1 day simulation of sea water quality can take in the range of 2 to 5 hours. Parallel computing and simulations running with graphic cards (that are usually more powerful compared to computer processors) significantly reduce running times.

8. Conclusions

Deep knowledge of the behaviour of crucial urban systems during crisis events (like extreme climate conditions) is essential for an adequate emergency management and for planning of risk reduction resilience measures. Decision support systems, numerical models and tools jointly to the new high capability of model software and hardware, have allowed to perform detailed simulations providing useful information concerning the system behaviour under certain conditions.

On the other hand, modern cities can be considered as complex systems of systems, so their resilience capacity is a holistic concept involving several fields (social, technological, economic and political among others) and several actors (public administrations at local and supramunicipal level, public and private companies and service managers). In this framework, full and detailed understanding of urban resilience needs the overcoming of sectorial analysis carried out, many times, in the different main city services.

RESCCUE project offers two different approach to fill this gap:

- A holistic analysis of city services focusing on their relations and interdependencies in case of extreme weather events (heavy storms, droughts, heat waves, wind storms, etc.) through HAZUR tool
- Advanced models and tools (and many times integrations of several detailed models) to describe specific cascading effects produced by extreme climate events (floods and droughts) on several urban services (water resources, receiving water bodies, urban drainage, electrical, transport and waste systems).

These first objectives of this deliverable have been the description of tasks related to sectorial models development (or updating in some cases) and their calibration and validation process (tasks carried out almost in all of cases with available field data). These sectorial models provide detailed information about the functioning of several urban systems (urban drainage, transport, waste, etc.) and their response under extreme climate pressures. Some of these models have been integrated in order to understand and analyse the relations among these models and the cascade potential cascade effects. This is the case of drainage-bathing water quality model for the detailed analysis of Combined Sewer Overflows (CSOs) in case of storm events, or the case of integrated flooding-transport models to represent surface traffic disruption due to heavy storm events producing surface flooding, or the case of flooding-waste models to show the potential effects of flooding on waste containers. Other integrated model has concerned local floods produced by failures in water supply system (pipe burst analysis). Moreover a detailed hydrological model, covering the whole Ter-Llobregat system in Catalonia, has been developed to analyse the effect of drought period in the water availability for the city of Barcelona. Finally a model to predict Llobregat river turbidity in the nearness of the Sant Joan Despí Water Treatment Plan on the basis of rainfall partners has been also developed.

Almost all these models have been calibrated and validates with a large set of collected field data and their reliability have been fully demonstrated. All these models/tools (integrated or not) allow the analysis of the relations among different urban services and the understanding of cascading effects introducing useful information to estimate the impacts.

The case of flooding integrated models is very exemplary. As said, several integrated models in the three RESCCUE cities concern flooding (sewer, river and tidal flooding) and the cascading effects produced by extreme events on strategic urban services.

The old 1D sewer and river flooding models only provided information about the state of the pipes or the reach during extreme events. This kind information was enough for urban drainage or river managers, but it is absolutely inadequate to manage city resilience and the potential impacts of flooding on other urban services. The use of the integrated flooding models allows the analysis of pedestrian and vehicular stability on surface (integration with 2D overland flow), the estimation of direct and indirect flood damage (integration with economic models to be done in Task 3.4 of WP3), the analysis of traffic disruption (integration with traffic model to be completed in Task 3.4 of WP3), the analysis of waste container stability (integration with waste container stability model), the analysis of pollutant in receiving water bodies (integration with marine model).

For the case of water resources and water supply, drought and potential pipe failures have been analysed. In the first case, hydrological model has been linked to the main reservoirs of the Ter-Llobregat system and allow to analyse their potential water deficits in case of drought. In the second case, water supply network has been analysed in order to check the potential consequences of a burst pipes using the 2D module of the coupled 1D/2D drainage model. The methodology carried out could be applied for all the critical points that are susceptible of failures due to several reasons (age, material, traffic load, previous problems, etc.).

All the sectorial and integrated models presented in this deliverable have been finally used to achieve hazard assessment of the system they simulate for the current scenarios. The same models will be used for the simulations related to future climate scenarios in order to estimate the potential effects of climate change (business as usual scenarios) and the effectiveness of adaptation measures (adaptation measures scenarios).

All the hazard maps produced (present, future and with adaptation measures) for the 3 case studies will be provided as an annex to D2.5.

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