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RESCCUE

RESILIENCE TO COPE WITH CLIMATE CHANGE IN URBAN AREAS

MULTI-HAZARDS ASSESSMENT RELATED TO WATER CYCLE EXTREME EVENTS FOR FUTURE SCENARIOS (WITH ADAPTATION STRATEGIES) PUBLIC VERSION

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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

2. Dissemination and uptake

   Public

3. Short Summary of results (<250 words)

   In the framework of WP2 of the RESCCUE project, Task 2.3 deals with the assessment of the effects of climate change scenarios and the analysis of the effectiveness of

adaptation measures in terms of hazard reduction. Deliverables 2.3 and 2.4 were devoted to present the main modelling results for Business as usual (BAU) scenarios, while this Deliverable (D2.5) is focused on the climate related hazards reduction through the implementation of those adaptation measures that can be modelled and whose effectiveness (in terms of hazard reduction) can be simulated through the detailed sectorial and integrated models developed in the WP2 for the three RESCCUE research sites. These scenarios considered the same climate change drivers provided by WP1 used for the simulations concerning Business as Usual scenario.
Hazard reduction has been expressed through graphs, tables and maps (commonly used for flood models) depending on the targets to be addressed and the selected hazard criteria.
Depending on the scope of the hazard analysis of each research site, adaptation measures have been proposed and simulated at local and city scales.
Results provided by these activities and included in this Deliverable will be used in WP3 to perform the assessment of risk reduction in the several impact models developed and used within RESCCUE project. Moreover simulation results will be also used to define key parameters for WP4 and WP5 (like city recovery time after a hazardous climate related event) to prioritize adaptation measures and to provide relevant inputs for Resilient Action Plans of the RESCCUE cities.

4. Evidence of accomplishment

   This report

Table of contents

Summary Tables

Summary Figures

1 Context description and introduction

1.1 Context

RESCCUE Work Package 2 (WP2) is focused on the climate-related hazard assessment concerning strategic urban services and environment. The first task of this WP (Task 2.1) was devoted to the identification of potential climate hazards for strategic urban services and infrastructures in the three research sites. The results of this task can be found in Deliverable 2.1 (Vela, 2017).

On the other hand, Task 2.2 provided a multi-hazard assessment in critical urban sectors for current scenario using detailed sectorial and integrated models. Specifically Task 2.2 involved the development / updating, calibration and validation of several models in the three RESCCUE research sites to be used for the simulation of the effects of some selected climate drivers on strategic urban services, infrastructures and the environment. The results of this task have been presented and summarized in Deliverable 2.2 (Russo, 2018a) and its public version Deliverable 2.4 (Russo, 2018b).

Task 2.3 deals with the assessment of the effects of climate change scenarios and the analysis of the effectiveness of adaptation measures in terms of hazard reduction.

The first phase of Task 2.3 concerned activity of simulations regarding the response of main critical services under climate change pressures provided by WP1. Deliverables 2.3 (Russo, 2019) presented the main modelling results for Business as usual (BAU) scenario at the three RESCCUE research sites.

In this Deliverable, multi-hazards related to BAU scenario are compared to current situation (baseline scenario). The results obtained in Task 2.3 for BAU and adaptation scenarios, like those obtained in D2.2 regarding the current state, are used to feed WP3 for the impact and risk assessment for current and future scenarios (WP3), as such as the resilience re-assessment of the three RESCCUE research sites (WP4).

2 Assessment of climate hazards reduction for Barcelona Research Site

2.1 Summary of multi-hazards and multi-risk assessment for Baseline and BAU scenarios

Barcelona, with a population of around 1,600,000 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 which could be more frequent according to climate change scenarios (Monjo *et al*., 2018). On the other hand, Barcelona and its metropolitan area are strongly depending on Ter and Llobregat reservoir systems to provide water demand throughout the year. The irregularity of the rainfall pattern in the whole catchments can produce drought events that could be exacerbated due to climate change (Monjo *et al.*, 2018). An Extreme Compass Rose for Barcelona regarding several weather variables is shown in Figure 1.

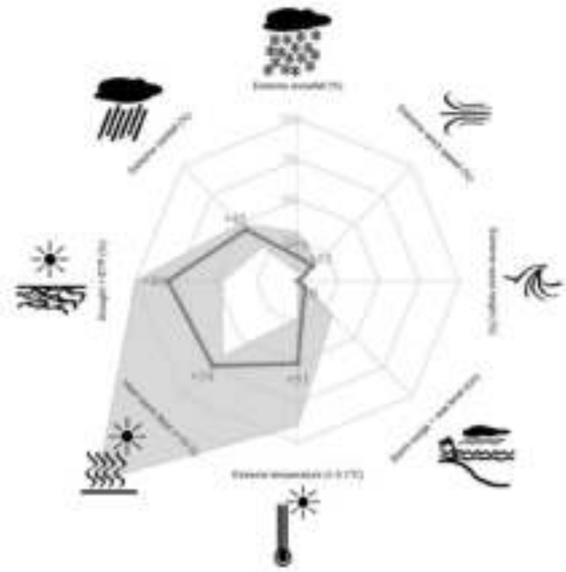


Figure 1: Extremes Compass Rose for Barcelona: Maximum point change in climate extreme events along the century taking into account return periods between 2 and 100 years. The centre represents no changes and the edge corresponds to an increase of 100% for every variable except, for heat wave days (border is +1000%) and extreme temperature (border is +10°C). Thick lines represent the median scenario and the shaded area is the uncertainty region (5-95%).

Within Task 2.1 of RESCCUE WP2, the main urban services of the city of Barcelona were fully characterized and critical weather variables potentially affecting them were defined ((Vela, 2017)). Moreover, a large set of weather variables were related to different natural hazards (drought, flooding, CSOs, water quality deterioration, heat waves, wind storms, storm surges, etc.) potentially affecting strategic urban services and these effects, in terms of hazards, were simulated in the context of Task 2.2. Particularly, in this task, the behavior of several urban services (urban drainage, traffic, electricity, solid waste, water supply, beaches) and critical infrastructures (like Sant Joan Despì treatment plant, electrical substations and distribution services) in case of extreme weather events (heavy rainfalls and drought) were analyzed through sectorial and integrated models developed and calibrated using a large set of field data (Table 1) (Russo, 2018a).

Table 1: RESCCUE sectorial and integrated models for Barcelona research site.

Urban 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
Coast	Coastal flooding**	Social and economic flood hazard and risk assessment concerning people, goods and properties
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

** For this model, BAU and Adaptation scenarios hazard simulations have not been performed due to the complexity to achieve and reflect climate change effects in the modelling simulations.*

*** For this model, Adaptation scenarios hazard simulations have not been performed due to the lack of adaptation measures proposed in the framework of RESCCUE project.*

On the other hand, in the first phase of Task 2.3, the multi-hazard assessment for the Business As Usual (BAU) scenario was carried out and comparative analysis among current (Baseline) and BAU scenarios were performed for each sectorial and integrated model related to Barcelona research site. Comparative results were expressed though maps, graphs and tables and, in many cases (mainly related to floods and drought), they showed significant increments due to climate change (Russo, 2019). Particularly, flood hazard showed high increments for all the analyzed urban services (urban drainage, surface transport, electrical system and waste collection), while simulations concerning drought model indicated significant hazard increments due to BAU scenario (respect to Baseline). On the contrary, water quality deterioration due to CSOs and turbidity (respectively for Barcelona beaches and Llobregat River) did not show significant variations for BAU (Figure 2).

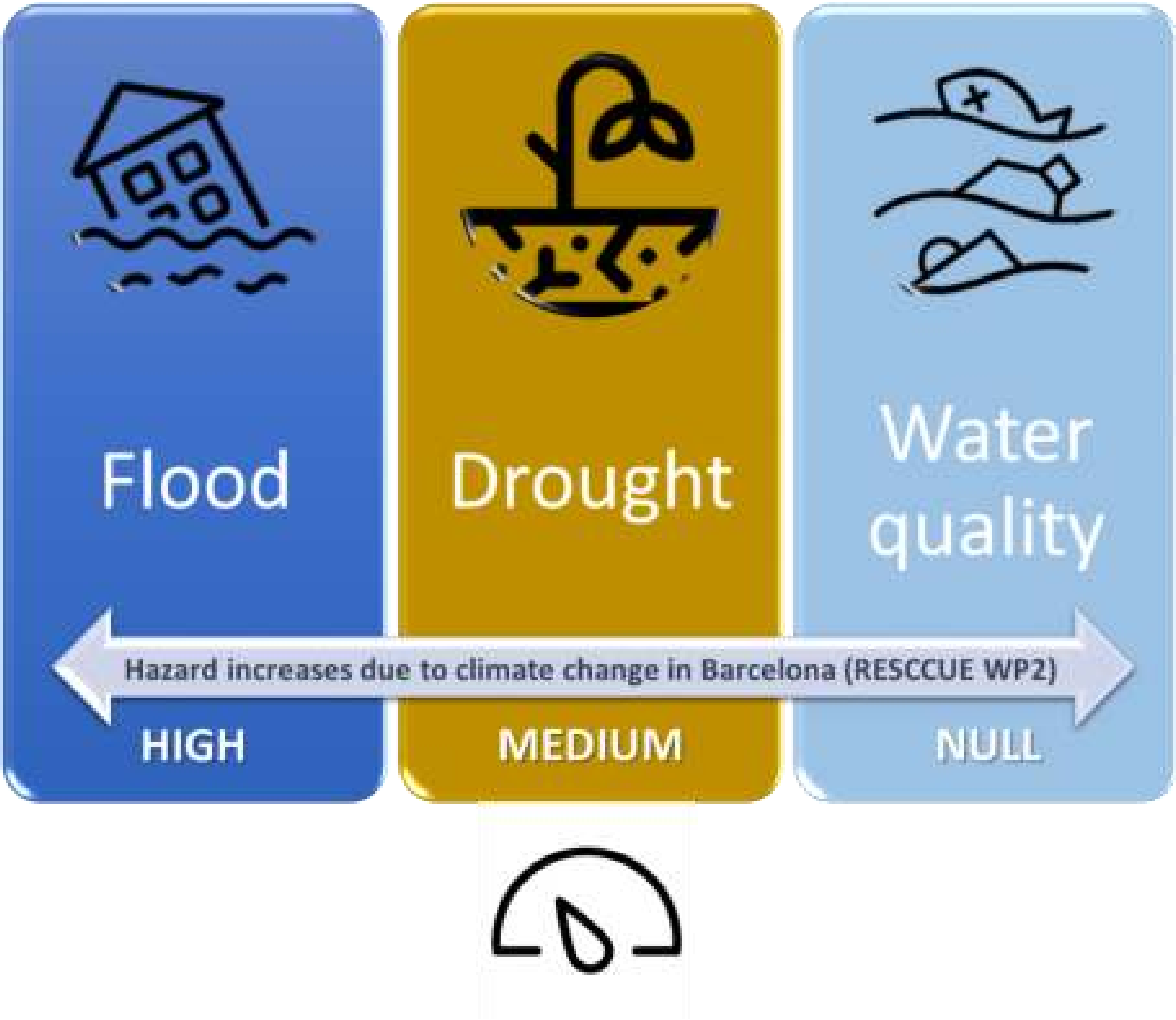


Figure 2: Summary of WP2 multi-hazard assessment and comparative analysis (Baseline vs. BAU scenario) for Barcelona research site.

Moreover, all the maps related to flood hazard will be used by Barcelona Municipality to feed the resilience platform of the city in order to help the planning and operation of the critical urban services to face with this threat.

2.2 Adaptation strategies and measures to cope with climate change for the city of Barcelona

According to Task 5.2 (WP5), a complete list of 15 strategies and related measures to cope with climate change in Barcelona has been proposed (Martínez‐Gomariz, 2019). 11 of these strategies were already included in the Barcelona Climate Plan of 2018 while other 4 were identified in the RESCCUE project according to the main notable changes expected for the future. For all of them a complete set of measures defines each strategy, which will be prioritized later according to the methodology proposed in WP5. The 4 strategies defined within RESCCUE to face with flood and drought problems potentially exacerbated by climate change are:

1. Flood impacts reduction in a context of climate change
2. Environmental improvement of receiving water bodies
3. Guarantee security service supply
4. Ensure the drinking water availability through alternative water resources

All these strategies have been fully analysed in the context of WP2, WP3 and WP5. Some of them (mainly related to flooding and CSOs problems) aim to reduce impacts acting on the hazard reduction, while other ones (mainly related to water resource guarantee) aim to minimize the vulnerability of the system promoting resilient measures. Hazard reduction for the first two strategies has been assessed using sectorial and integrated models described in the previous deliverables of WP2 defining, for each of them, two different adaptation scenarios according to the progressive implementation of selected adaptation measures. For these two strategies, the assessment of the hazard reduction due to the implementation of a set of measures will be fully described in the following sections.

Flood impacts reduction in a context of climate change (short name “Flooding strategy”)
- Flooding adaptation scenario 1
- Flooding adaptation scenario 2

Environmental improvement of receiving water bodies (short name “CSOs strategy”)
- CSO adaptation scenario 1
- CSO adaptation scenario 2

Adaptation scenarios 1 for each strategy includes the same measures. These are sustainable urban drainage solutions (SUDS) defined as infiltration trenches, green roofs and upstream catchment retention tanks. More detail on these infrastructures is provided in chapter 2.3.2. Adaptation scenarios 2 for each strategy include the SUDS measures from adaptation scenario 1 plus structural measures:

Flooding adaptation scenario 2 includes structural measures to avoid flooding according to the design criteria defined. These structural measures are mainly detention tanks and new pipes in the primary sewer network of the city. The design criteria as well as these structural measures are defined in chapter 2.3.2.
CSO adaptation scenario 2 includes structural measures to reduce CSO flows and its impact in the receiving waters (bathing areas, river and harbor) according to the design criteria defined. These structural measures are CSO tanks. The design criteria as well as the description of the structural measures are defined in chapter 2.7.2

On the other hand, adaptation strategies and measures affecting vulnerability and resilience of the considered Barcelona urban critical services within RESCCUE will be fully analysed in WP3.

2.3 Urban Drainage Sector

2.3.1 Introduction and summary of climate hazards for the urban drainage sector

Deliverable 2.3 Multi-hazards assessment related to water cycle extreme events for future scenarios - Business As Usual presented the sewer model characteristics as well as the main simulation and hazard assessment results for the Baseline and the Business As Usual (following BAU) scenarios, as such as comparative analysis (Russo, 2019).

In this chapter a brief summary with the relevant information is presented.

A full network (primary and secondary sewers) model is created and coupled with a 2D overland model creating a very accurate overland mesh covering the whole city. The Table below presents a summary of the main features of the model.

Table 2: Summary of the model elements.

Model element	PDISBA model
Nodes (manholes, inlets, grates, etc.)	85835
Storage nodes (tank bodies)	284
Nodes outfalls	619
Pipes	89465
Pumps	75
Sluices	44
Weirs	980
2D mesh triangles	1361324

This model was calibrated and validated presenting very good correlations as seen in Figure 3.

The following step was to run the model for Baseline and BAU scenarios using current design rainfall events for different return periods (T1, T10, T50, T100 and T500) (Baseline) and with the climate change rainfall events (BAU) applying the specific climate change factors (for each return period and duration) provided by WP1 (Monjo *et al.*, 2018).

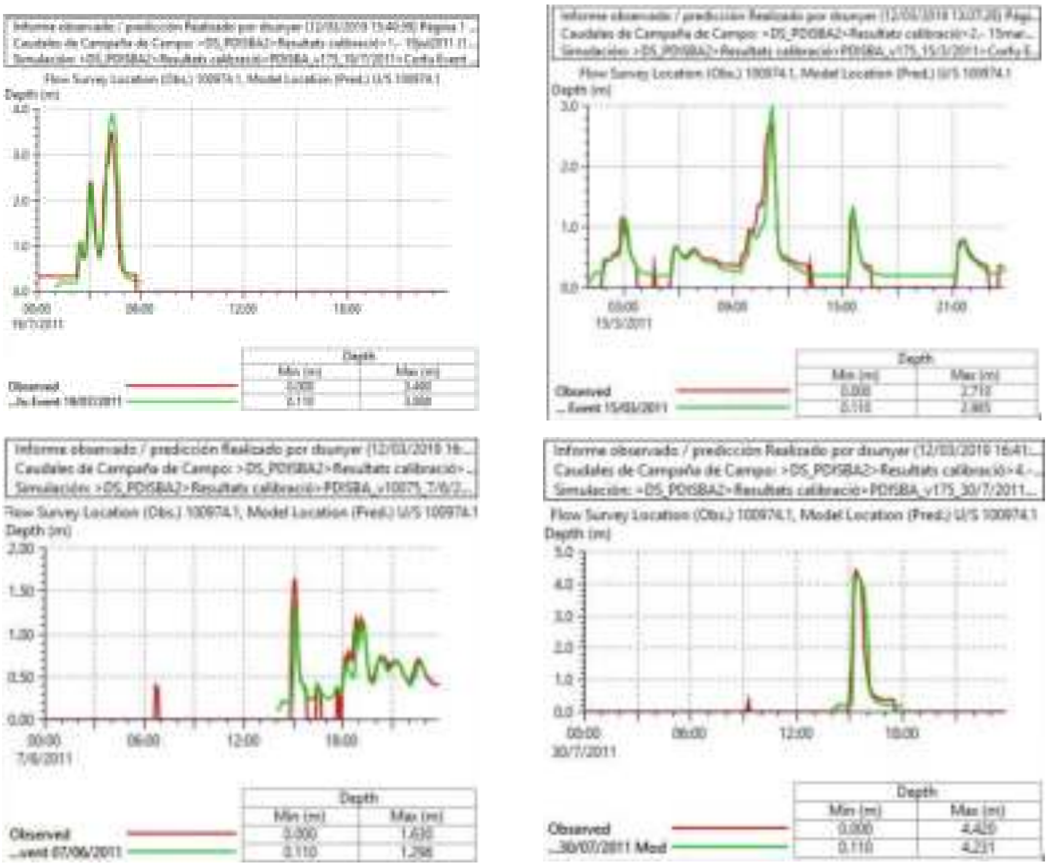


Figure 3: Calibration and validation results for limnimeter CL205 in Paral·lel street for the 4 rainfall events used for calibration and validation processes.

Table 3: Comparison between maximum 5 minutes rainfall intensities for BAU and current scenarios for different synthetic rainfall events. Rainfall durations is 2 hours and a half which is important to compute the rainfall volume (V) in the table.

Return period	Rainfall for climate change scenarios		Rainfall for current scenario	
	Imax (mm/h)	V (mm)	Imax (mm/h)	V (mm)
T1	73.78	24.07	63.60	22.17
T10	196.66	88.36	177.17	83.72
T50	234.56	112.88	217.19	104.15
T100	256.42	127.25	239.64	115.81
T500	312.09	157.21	291.67	143.41

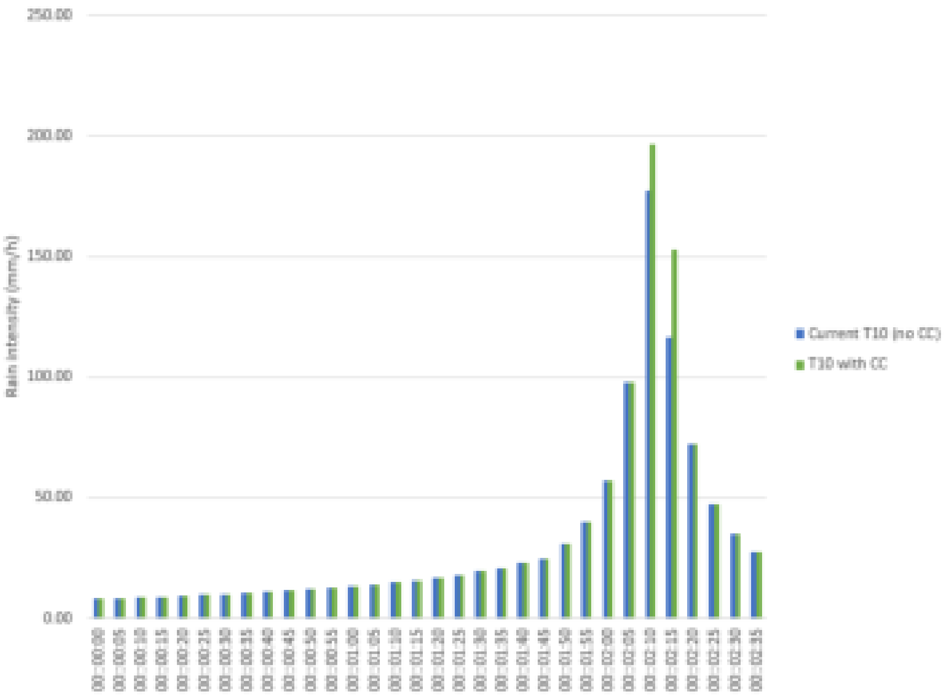
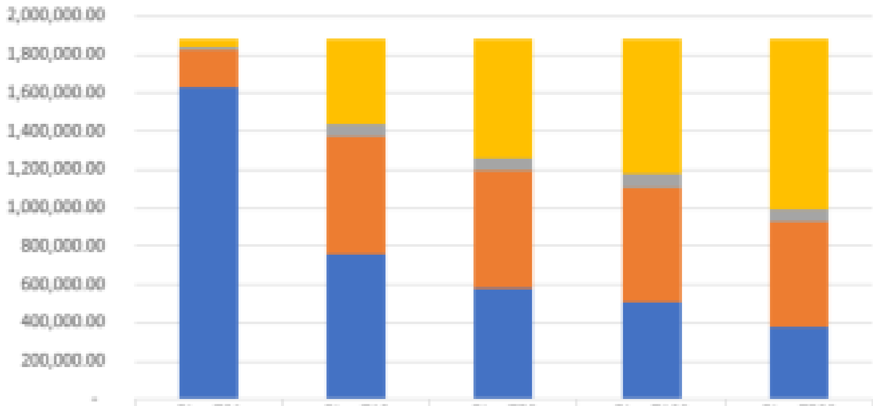


Figure 4: Comparison between the design project storm for the Baseline (T10) and the future scenarios (T10 CC) corresponding to the time period 2071-2100.

Once the model was run for both scenarios and the different return period rainfall events, results were computed for:

- Pipe functionality: Showing the pipes with water above ground, the ones in pressure flow and the ones in free flow
- Pedestrian hazard: Showing the areas with high, medium and low hazard
- Vehicular hazard.

Next figures present some of the results obtained.



	Diag T01	Diag T10	Diag T50	Diag T100	Diag T500
4-Water above ground	45,981.61	445,802.80	628,083.05	708,228.79	889,558.13
3-0.5 m below ground	10,003.62	63,930.68	66,397.91	67,714.30	66,163.59
2-Pressure flow	201,259.83	618,323.64	614,316.46	604,015.41	551,313.99
1-Free flow	1,628,413.28	757,601.22	576,860.93	505,699.84	378,622.63

1-Free flow   2-Pressure flow   3-0.5 m below ground   4-Water above ground

Figure 5: Pipe functionality results for T10 for current scenario (meters of pipe).

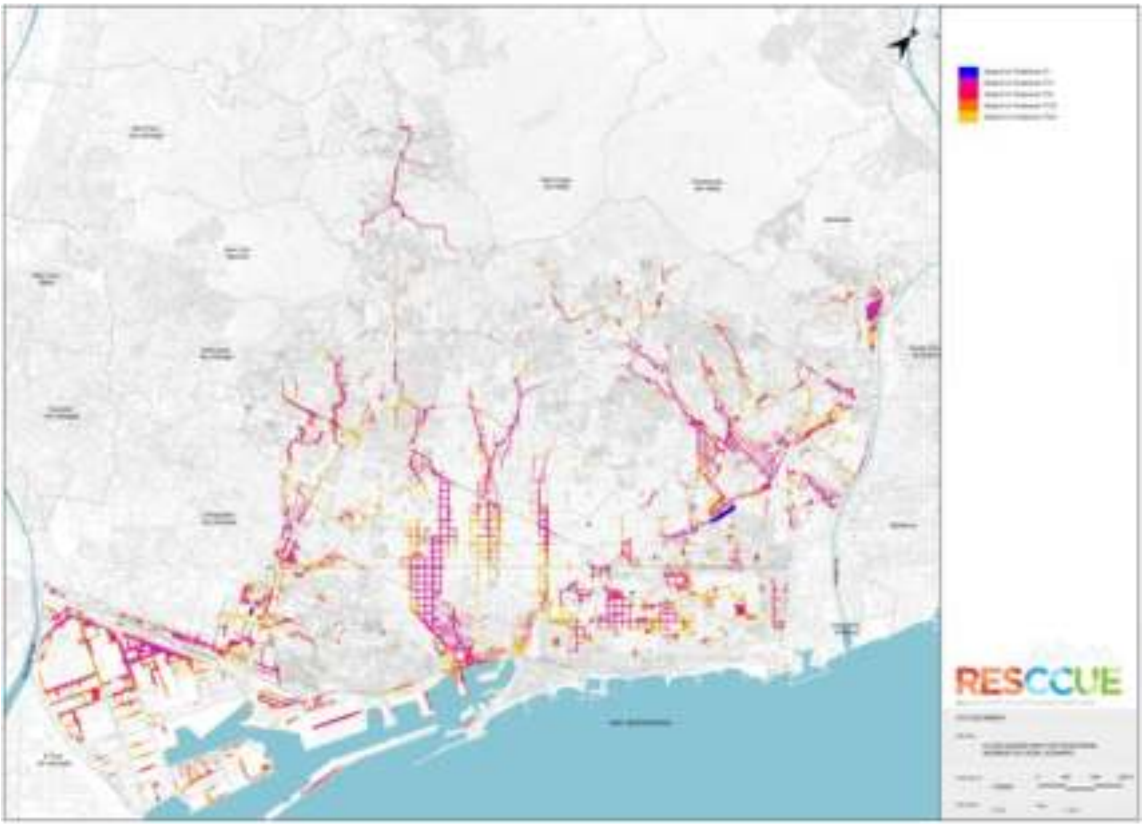


Figure 6: Pedestrian high flood hazard results for BAU scenario for all the simulated return periods.

2.3.2 Adaptation strategies, measures and design criteria

As previously said, within RESCCUE, 4 new strategies were defined to face with flood and drought problems that, accordingly with WP1 results, could be potentially exacerbated by climate changes.

Two of these strategies are directly related to the urban drainage sector:

- Flood impacts reduction in a context of climate change
- Environmental improvement of receiving water bodies, focused on Combined Sewer Overflows (CSOs) reduction

For the first strategy, the assessment of the hazard reduction due to the implementation of a set of measures is fully described in the following sections, while the modelling and hazard assessment activity related to the CSOs reduction strategy are presented in the section regarding beach sector.

As said, several adaptation scenarios within flood reduction strategies including Sustainable Urban Drainage Systems (SUDS) and structural measures have been also defined as following:

Flood impacts reduction in a context of climate change (short name "Flooding strategy")

- Flooding adaptation scenario 1
- Flooding adaptation scenario 2

General description of the measures

The following types of measures are listed and described below:

SUDS:

The Technical Plan for the Use of Alternative Water Resources in Barcelona, already plans Sustainable Urban Drainage Systems (SUDS). These systems are very beneficial for the sewerage system because they reduce the runoff volume and peak flows that reaches the sewer. These combined effects have benefits both to reduce floods and to reduce CSOs.

New primary collectors and associated works:

They include, in general, those that are essential, and generally urgent, for the elimination of floods still occurring in some areas of the city. These are new works in the combined network improving the capacity for transport, storage and / or management of the network

Flood tanks:

They are also essential, and in general urgent, for the elimination of floods still occurring in some areas of the city, while they also serve, in many cases, to reduce CSO volumes into receiving waters.

Other measures considered in the Barcelona Drainage Master Plan but not evaluated in RESCCUE are:

- New inlets and improvement of the existing ones
- Expand centralized operation
- Improve secondary sewer network
- Rehabilitation and maintenance actions

Adaptation strategies and measures implemented

Two main adaptation scenarios have been considered within the “flood reduction strategy”:

- Flooding adaptation scenario 1
- Flooding adaptation scenario 2

Flooding adaptation scenario 1 considers the full implementation of SUDS planned for the whole Barcelona city. These measures are shown in Figure 7.

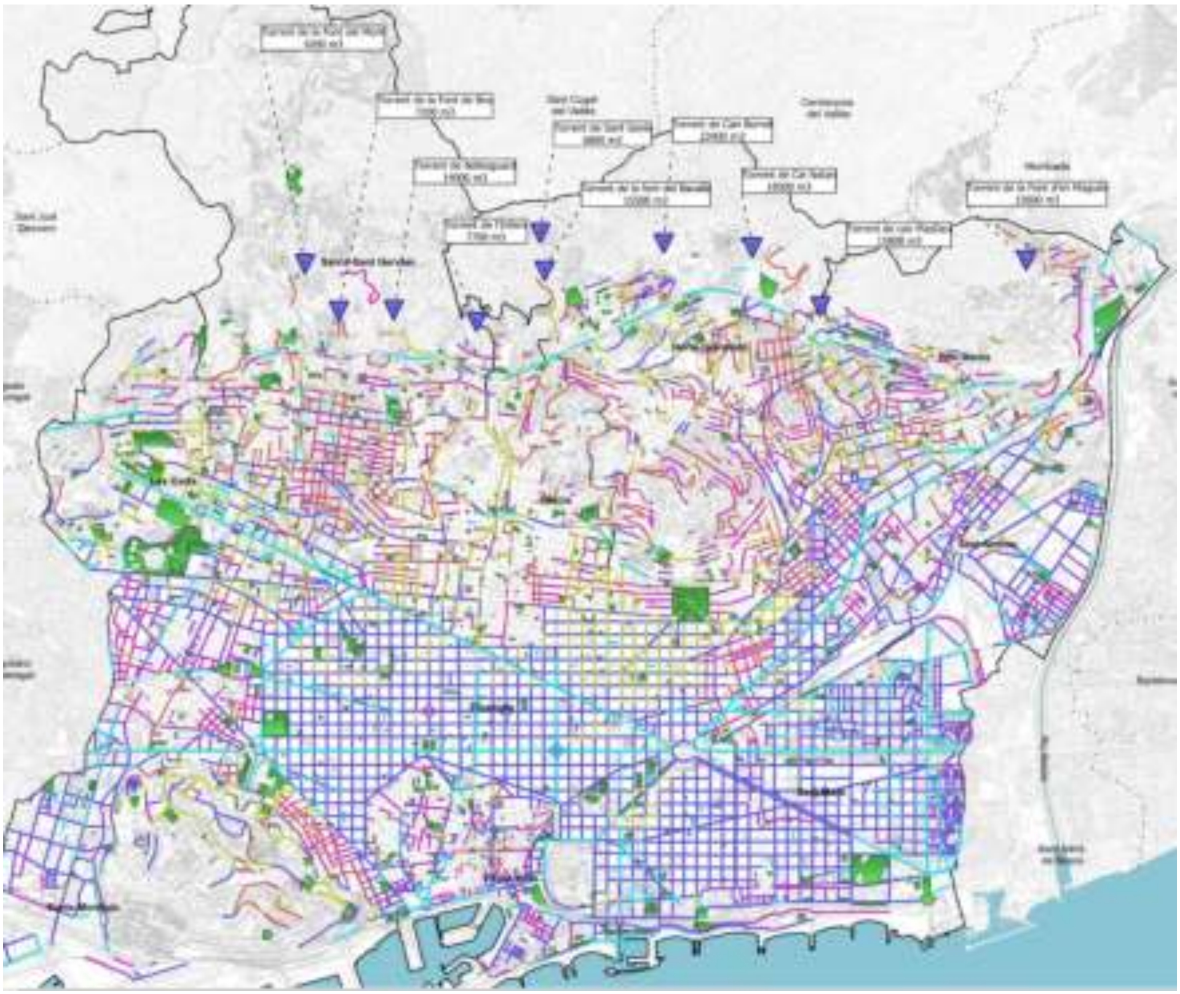


Figure 7: SUDS measures planned in the PDISBA and implemented in the scenario 1

There are mainly 3 types of SUDS planned.

Infiltration trenches: These are described and planned in The Technical Plan for the Use of Alternative Water Resources in Barcelona and are divided in 5 main types according the street width and slope.
Upstream catchment retention basins. These are located in the main rural catchments upstream of the city and are designed to retain the 10 year return period.
Green roofs. The location and description of the green roofs planned in Barcelona has been obtained from the Covered and Green Walls document in Barcelona provided by the Barcelona City Council within the framework of the CORFU project (Donna Sto. Domingo *et al.*, 2014).

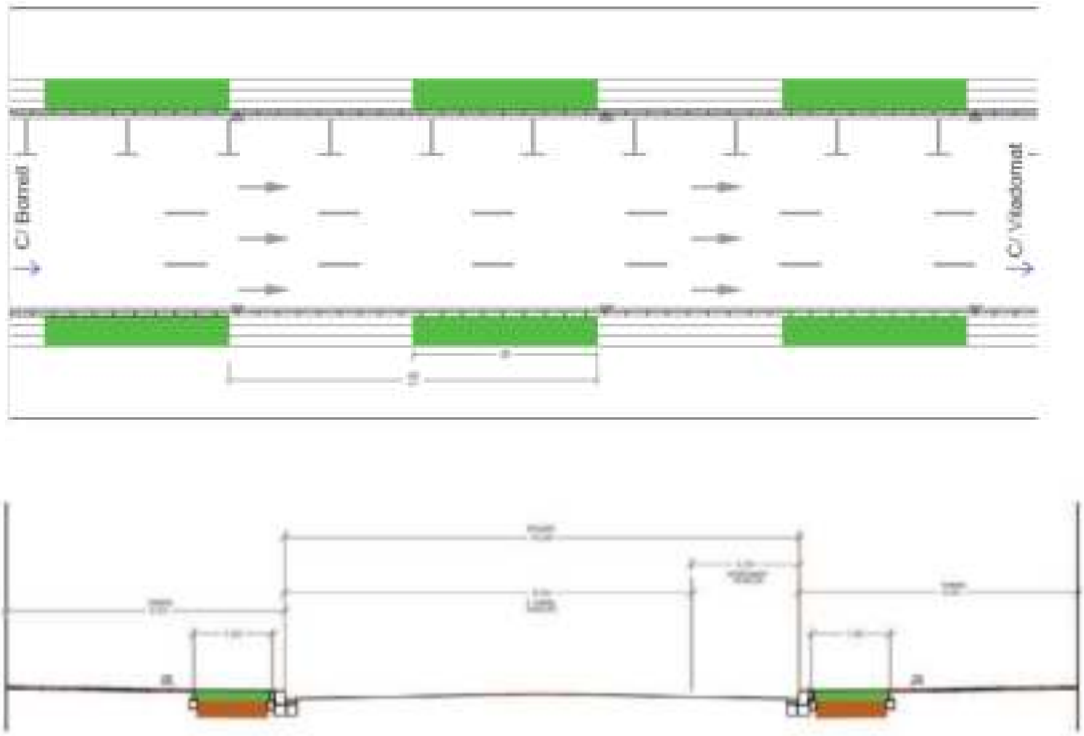


Figure 8: Example of infiltration trench planned for Mallorca Street (type 2).

Table 4: Volumes of the dentention and retention basins considered in the Barcelona Drainage Master Plan (PDISBA) and RESCCUE project.

Code	Nme	Catchment area (ha)	Tank volume (m^3)
33	Torrent de can MasDeu	69.8	15800
24	Torrent de Can Borrell	84.54	23400
43	Torrent de la font del Bacallà	60.97	15500
22	Torrent de Cal Notari	69.6	18500
49	Torrent de la Font d'en Magués	51.87	15600
19-20-21	Torrent de Bellesguard	36.05	14000
46-47	Torrent de la Font de Bou	23.91	7200
62	Torrent de l'Infern	25.77	7700
54	Torrent de la Font del Mont	12.3	4200
77-78	Torrent de Sant Genís	18.65	6800

Flooding adaptation scenario 2 includes the SUDS measures described for the scenario 1 as well as the structural measures required to fulfill the flooding design criteria.

Flooding design criteria

The flooding design criteria implemented in RESCCUE are the ones fixed by BCASA in the Urban Drainage Master Plan (PDISBA):

Sewer network should operate in free flow conditions for the 10 years return period design rainfall taking into account the effects of climate change on maximum intensities.
When the excessive cost justifies it, a less restrictive criterion will be implemented. This implies that the street does not flood for the 10 years return period design rainfall taking into account the effects of climate change on maximum intensities.
Finally, when the cost of the measures to fulfill the previous design criteria is excessive, a less restrictive criterion can be considered. This is that the pedestrian hazard level is not high according to the definition provided in deliverable 2.3 and presented below for the 10 years return period design rainfall taking into account the effects of climate change on maximum intensities.

Table 5: Definition of pedestrian hazard levels (Martínez-Gomariz, Gómez and Russo, 2016).

Pedestrian hazard level	Definition
High	Flow depth > 0.15 m or Flow velocity > 1.88 m/s or Flow depth · Flow velocity > 0.22
Medium	Flow depth < 0.15 and Flow velocity < 1.88 and 0.16 < Flow depth · Flow velocity < 0.22
Low	Flow depth < 0.15 and Flow velocity < 1.88 and Flow depth · Flow velocity < 0.16

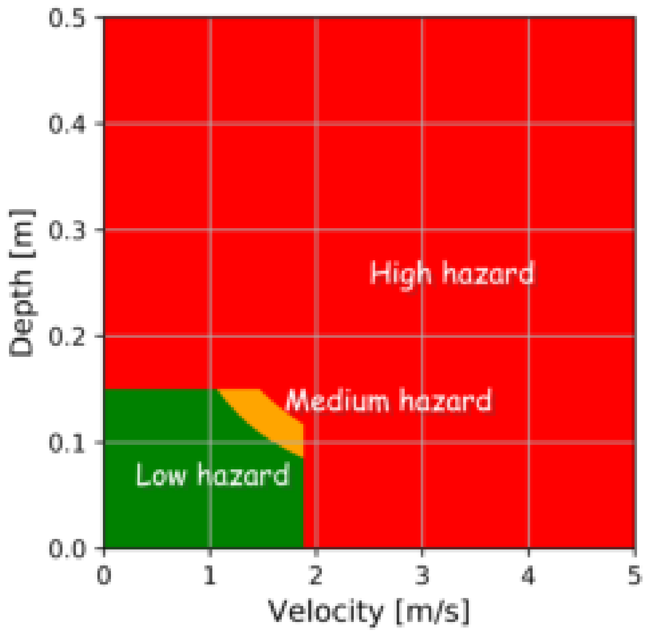


Figure 9: Pedestrian hazard levels (Martínez-Gomariz, Gómez and Russo, 2016).

2.3.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

Model description for the adaptation scenarios

Several changes have been applied to the Baseline and BAU model to implement the described adaptation measures. A brief summary is presented here for each adaptation scenario.

<u>Adaptation scenario 1 (SUDS measures)</u>

- As mentioned, the starting model is the correctly calibrated 1D-2D model used for Baseline and BAU scenarios.
- The infiltration trenches and the green roofs are incorporated into the model by calculating the surfaces of each one and creating a specific runoff surface with manually adjusted Horton infiltration parameters to reproduce the behavior of these elements (see Figure 10).
- The Upstream catchment retention basins are modelled as regular basins storing rainwater to be used for other uses or draining it in a controlled and attenuated manner. The volume of these basin is configured so that for the rain of T = 10 years return period with climate change the basin is filled to 100% with the runoff generated in its upstream catchment.

Propiedades de la Superficie de Escorrentía	
Superficie de Escorrentía ID	32
Descripción	Teulades verdes
Tipo de Superficie	Pervious
Tipo de Tránsito de Escorrentía	Abs
Valor del Tránsito de Escorrentía	0.200
Pendiente del Terreno (m/m)	0.000000
Tipo de Volumen de Escorrentía	Horton
Tasa de Infiltración Inicial Horton (mm	76.000
Tasa de Infiltración Final Horton (mm/l	0.000
Constante de Decaimiento de Horton	4.140
Porosidad Inicial para Pérdida	1.000
Tipo de Pérdida Inicial	Abs
Valor de la Pérdida Inicial (m)	0.00028000
Constante de Recuperacion de Hortor	0.036
Modelo de Tránsito	SWMM

Propiedades de la Superficie de Escorrentía	
Superficie de Escorrentía ID	31
Descripción	SUDS
Tipo de Superficie	Pervious
Tipo de Tránsito de Escorrentía	Abs
Valor del Tránsito de Escorrentí	0.200
Pendiente del Terreno (m/m)	0.000000
Tipo de Volumen de Escorrentía	Horton
Tasa de Infiltración Inicial Horto	100.000
Tasa de Infiltración Final Hortor	37.000
Constante de Decaimiento de H	4.140
Porosidad Inicial para Pérdida	1.000
Tipo de Pérdida Inicial	Abs
Valor de la Pérdida Inicial (m)	0.00028000
Constante de Recuperacion de I	0.036
Modelo de Tránsito	SWMM

Figure 10: Runoff Surface parameters defined to model green roofs (left) and infiltration trenches (right), in Spanish. The green roof area is approximately 143 ha and the infiltration trench 181 ha (note that the trenches receive stormwater runoff from a larger area).

<u>Adaptation scenario 2.- SUDS and structural measures</u>

- This scenario includes the SUDS measures, so in this case the starting model is the one of the adaptation scenario 1 described previously.
- The structural measures planned are focused on the primary sewer network of the city assuming that floods on the secondary axes are already resolved. The way to incorporate this hypothesis into the model is to assume that the entire secondary network has enough capacity to avoid flooding. This hypothesis has its importance in the analysis of the results of the models and the cost-benefit analysis, as there is a part of the reduction of floods between scenarios 1 and 2 that are not directly produced by structural actions planned but by this increased capacity of the secondary network.

- The structural measures that were pending to construct from the previous Master Plan, the PICBA'06, have been incorporated in the model and it is verified that these actions are not sufficient to solve the flooding problems. One of the main causes of this is that the design rainfall of the PDISBA is much greater than the previous Barcelona Directors Plans (in maximum intensities and especially in volume). Some of these structural measures included here are:
    - New Diagonal street sewer to double its capacity.
    - Navas tank with a volume of 17000 m^3
    - Hospital Militar tank with a volume of 27000 m^3
    - Sagrera – AVE tank with a volume of 90000 m^3
    - Estatut parc tank with a volume of 12100 m^3
- New measures are necessary to achieve the defined protection objectives and they are introduced in the model. Many of these new actions are tanks. The reason is that with the chosen design rainfall the whole network goes to the limit of its capacity, so that increasing the existing network sewer capacity only causes that the problem downstream is worsen. Generally, these new tanks are simulated as off-line ones (see Figure 11) so that they are filled only when the sewer network downstream the tank does not have enough capacity for the peak flows. The total amount of structural measures implemented and simulated in the model has been 274 (among new pipes, tanks, weirs, etc.).

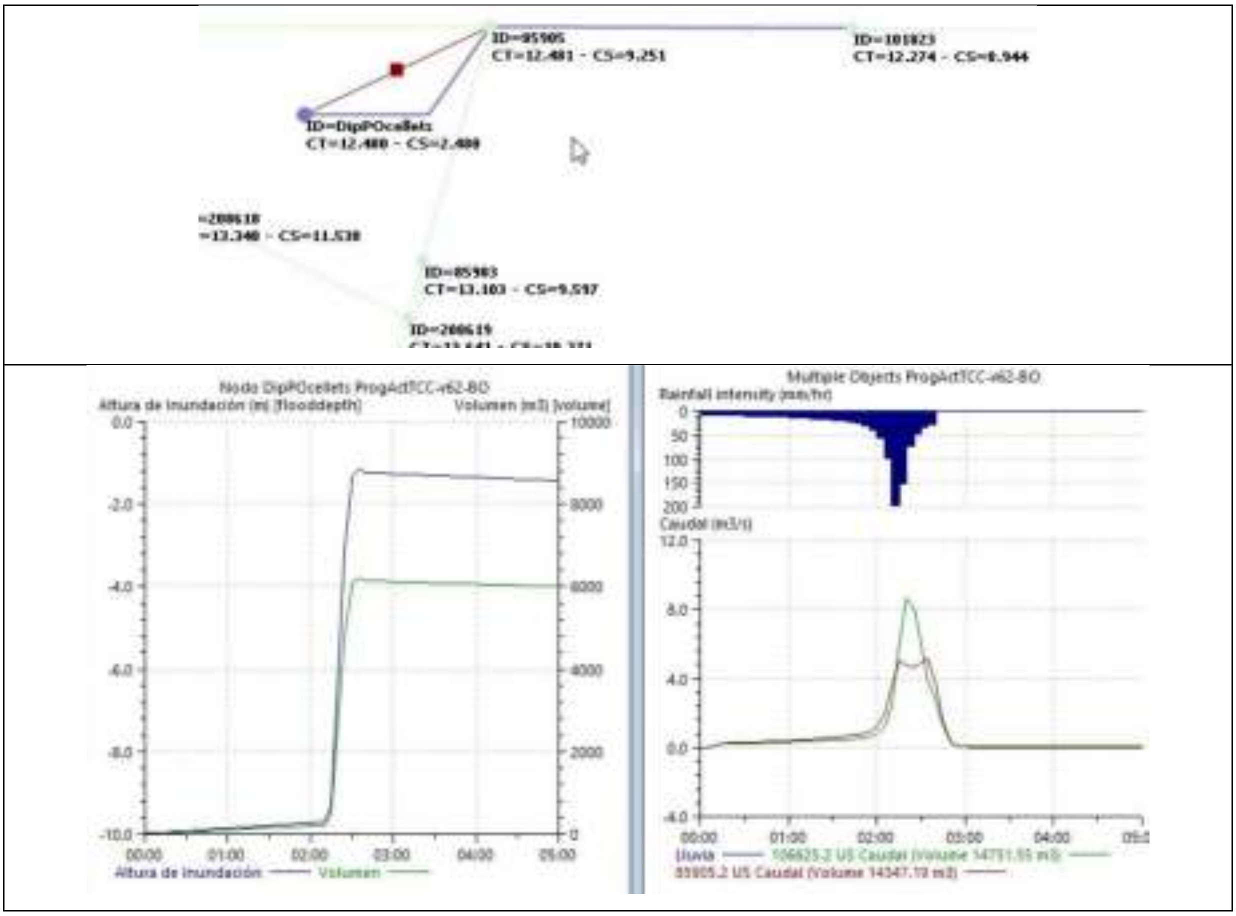
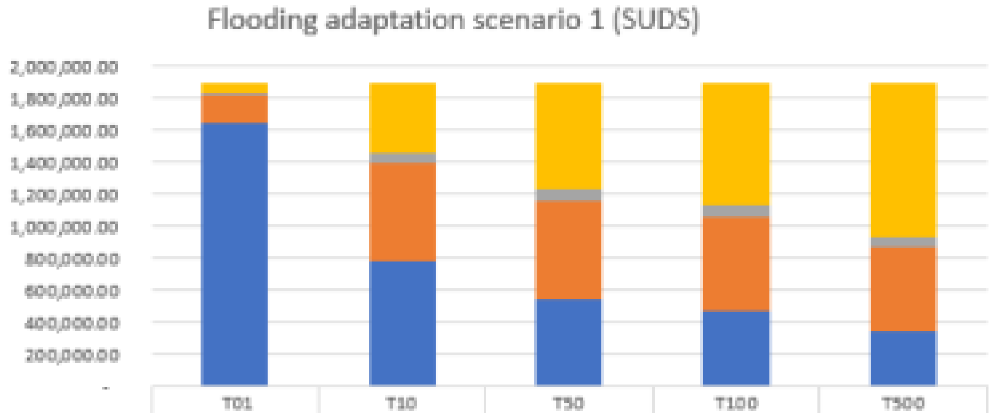


Figure 11. Example of the off-line tank modelled in the Ocellets square (Paral·lel) and results for the 10ys return period rainfall event with climate change.

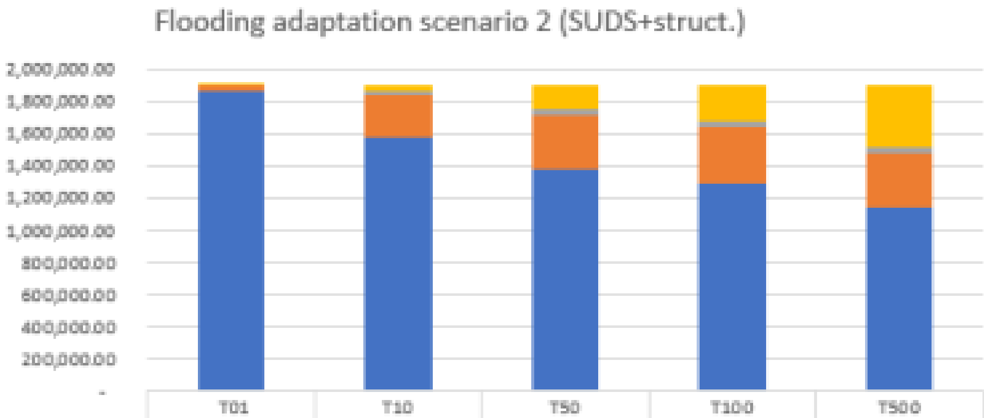
Model results for the adaptation scenarios

For each of the two described adaptation scenarios, the design rainfall events for 1, 10, 50, 100 and 500 years return period with climate change are modelled and the results in terms of pipe functionality, pedestrian and vehicular hazard for each Barcelona district and the whole city are provided for each one.



Flooding adaptation scenario 1 (SUDS)	T01	T10	T50	T100	T500
4-Water above ground	52,357.50	430,682.16	660,381.01	757,492.68	948,834.65
3-0.5 m below ground	11,633.22	62,155.15	69,166.64	67,685.06	70,478.39
2-Preasure flow	182,316.40	615,473.05	611,547.31	594,643.71	525,319.44
1-Free flow	1,640,705.50	780,700.27	545,895.66	467,169.16	342,358.15

Figure 12: Sewer functionality results for flooding adaptation scenario 1 (in meters of pipe).



Flooding adaptation scenario 2 (SUDS+struct.)	T01	T10	T50	T100	T500
4-Water above ground	6,560.40	47,244.55	160,168.13	234,524.61	393,996.62
3-0.5 m below ground	706.53	14,301.25	27,829.23	32,483.02	36,237.47
2-Preasure flow	30,100.02	263,066.76	337,502.63	349,608.32	334,126.05
1-Free flow	1,868,103.18	1,580,857.56	1,379,970.13	1,288,854.17	1,141,109.98

Figure 13: Sewer functionality results for flooding adaptation scenario 2 (in meters of pipe).

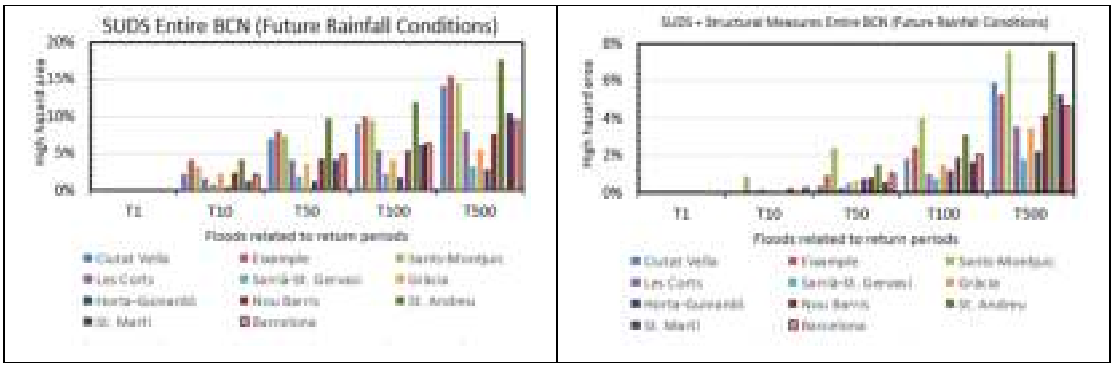


Figure 14: High Hazard pedestrian areas for adaptation strategies 1 (left) and 2 (right).

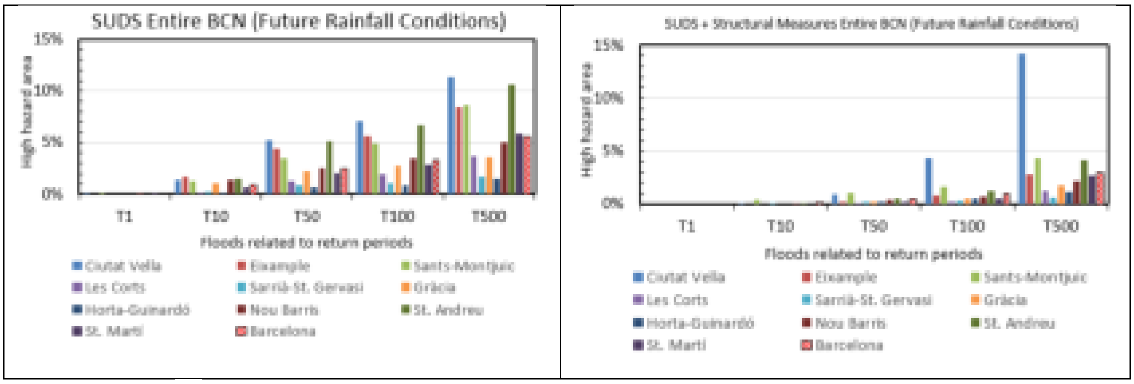


Figure 15: High Hazard vehicular areas for adaptation strategies 1 (left) and 2 (right).

Results comparison with BAU scenario

Finally in the figures below the previous results are compared with the BAU scenario. It can be seen an important decrease of malfunction of the sewer system (in terms of water above ground for sewer functionality or high hazard for pedestrians and vehicles) due to the implementation of SUDS, although the biggest reductions (above 90%) are given for the adaptation scenario 2 (SUDS and structural measures) and for the 10 year return period results which is the defined design criteria.

Scenario	1-Free flow	2-Preasure flow	3-0.5 m below ground	4-Water above ground
Business as usual	672,738.99	623,618.43	65,936.03	523,364.89
Flooding adaptation scenario 1 (SUDS)	780,700.27	613,473.03	62,135.15	430,682.16
Flooding adaptation scenario 2 (SUDS+struct.)	1,580,857.56	263,066.76	14,301.25	47,244.55

Figure 16: Comparison of the 10 years old return period results for the 3 scenarios in terms of sewer functionality (sewer length in m).

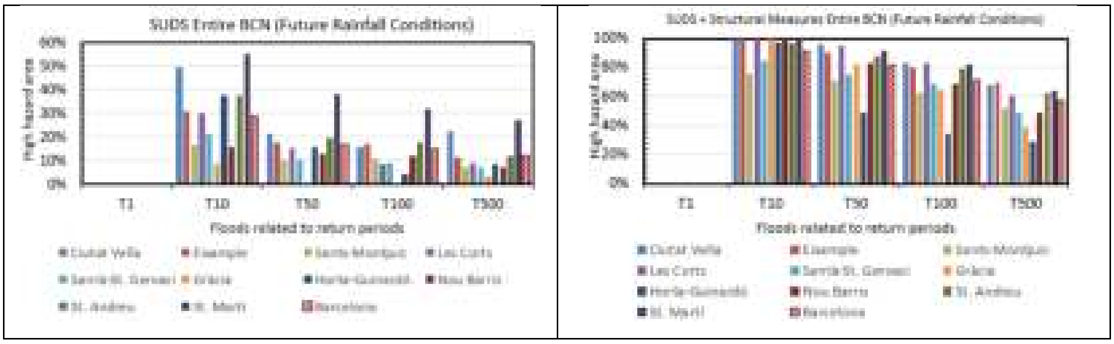


Figure 17: Percentage reduction of the pedestrian hazard area for adaptation scenario 1 (left) and 2 (right) compared to the BAU scenario results.

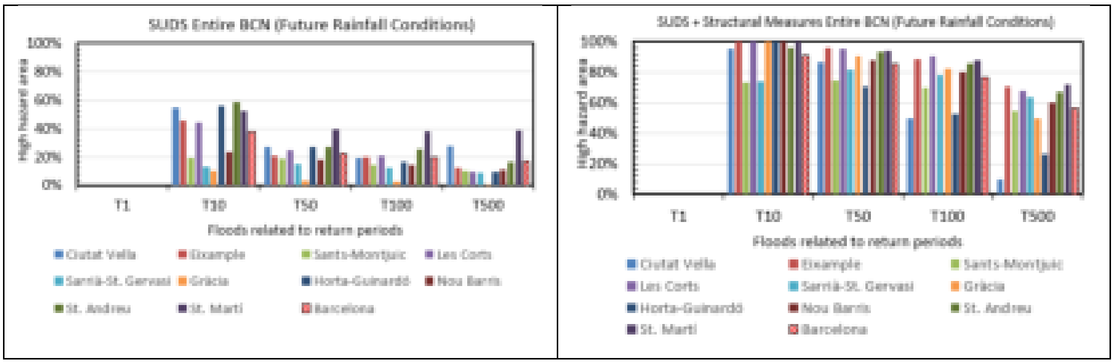


Figure 18: Percentage reduction of the vehicular hazard area for adaptation scenario 1 (left) and 2 (right) compared to the BAU scenario results.

2.4 Traffic sector

2.4.1 Introduction and summary of climate hazards for the traffic sector

As discussed in Deliverables 2.2 (Russo, 2018a) and 2.3 (Russo, 2019) the properties of the roads/link sections for the meso-scale traffic model within the TransCAD software are amended in relation to the flood depths along the links. The process of generating the hazard maps that represent the hazards posed to traffic flow in respect to flood depths are shown in Figure 19.

For both Baseline and BAU scenarios, the streets of the city of Barcelona (around 1472 km) have been analysed to detect potential traffic problems due to flood produced by heavy storm events.

Table 6: Parameters for defining effect of flood depths on traffic speed limits within TransCAD.

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

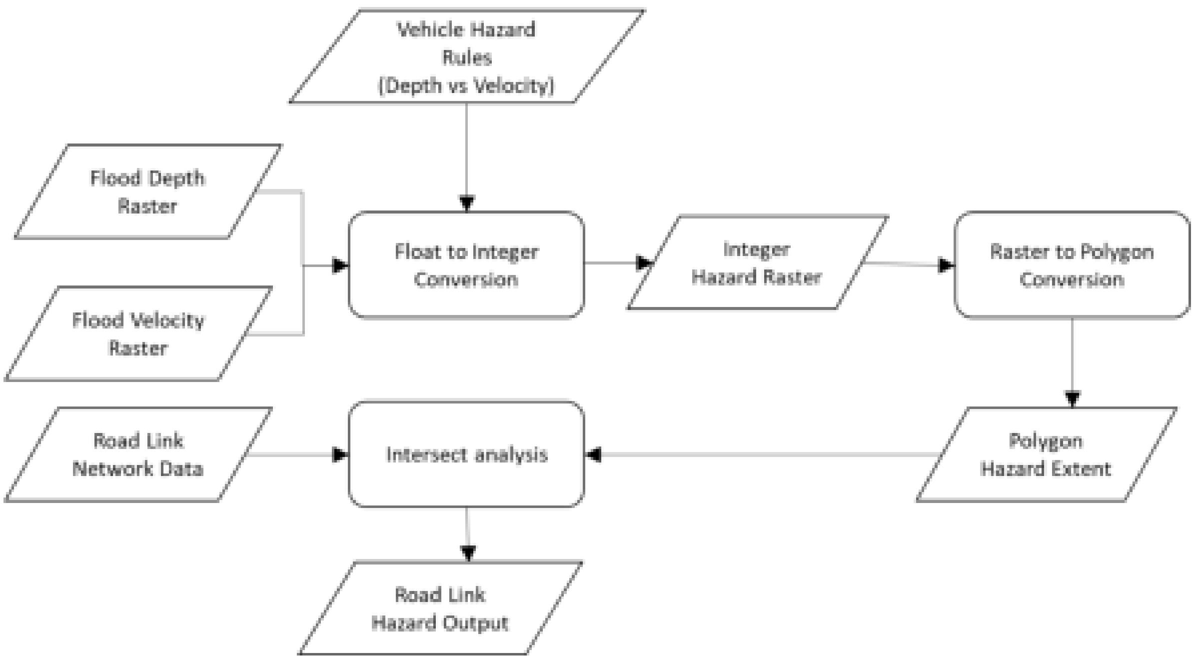


Figure 19: Methodology for generating hazard map outputs for load links based on flood depth data.

2.4.2 Adaptation strategies and measures and design criteria

The flood hazard reduction due to the implementation of the adaptation measures (SUDS and Structural measures) was assessed for both flooding adaptation scenarios previously described.

So, the same adaptation strategy and measures have been considered to assess flood hazard in terms of traffic disruption. Also design criteria were the same described for the urban drainage sector.

2.4.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

Hazard assessment and hazard maps elaboration were performed or the Flooding adaptation scenario 1 (application of SUDS with climate change conditions) and Flooding adaptation scenario 2.

Table 7, Figure 20 and Figure 21 show the results for the 10, 50, 100 and 500 year return period (events for 1 year return period provided very few traffic affections) for the two adaptation scenarios and the comparative analysis respect to Baseline and BAU scenarios.

Table 7: Summary of the impacts of pluvial flood in Barcelona for several return periods (T10, T50, T100 and T500) and all the analyzed scenarios (Baseline, BAU, Adaptation 1 and Adaptation 2 scenarios.

Scenario	Links with limited velocity (km)	Closed links (km)	Links with limited velocity (%)	Closed links (%)
Baseline_T010	223	170	15%	12%
Baseline _T050	310	266	21%	18%
Baseline _T100	330	324	22%	22%
Baseline _T500	377	437	26%	30%
BAU_T010	269	201	18%	14%
BAU_T050	344	336	23%	23%
BAU _T100	372	390	25%	26%
BAU_T500	401	517	27%	35%
Adaptation1_T010	224	155	15%	11%
Adaptation1_T050	325	288	22%	20%
Adaptation1_T100	352	346	24%	24%
Adaptation1_T500	403	473	27%	32%
Adaptation2_T010	37	24	3%	2%
Adaptation2_T050	138	84	9%	6%
Adaptation2_T100	190	129	13%	9%
Adaptation2_T500	269	264	18%	18%

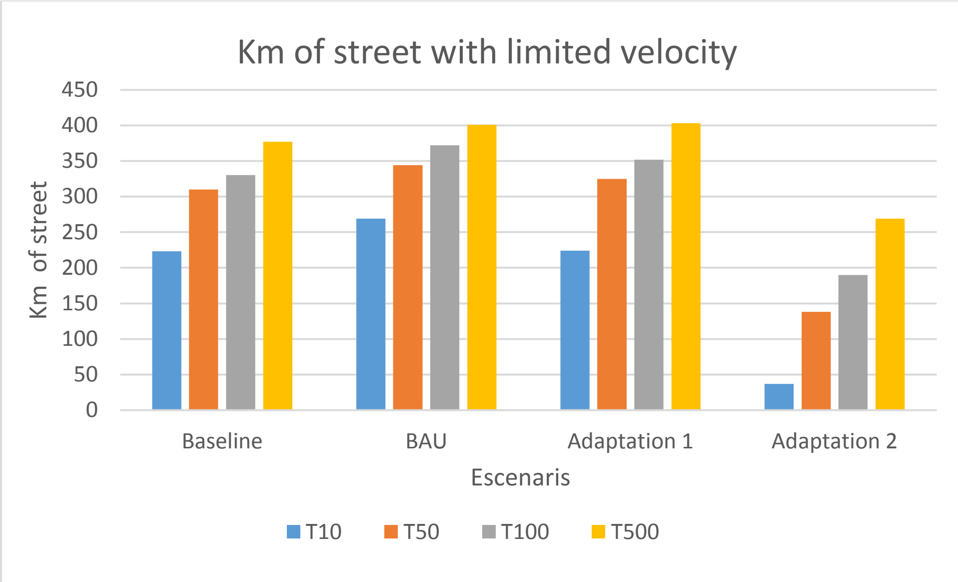


Figure 20: Km of streets with limited velocity due to pluvial flooding in Barcelona depending on the considered return periods and simulation scenarios.

Figure 21: Km of closed streets due to pluvial flooding in Barcelona depending on the considered return periods and simulation scenarios.

For all the performed simulations, specific hazard maps have been developed. Some examples are shown in the following figures. This type of information is used to feed the traffic model managed by the Barcelona city mobility department to evaluate the increase of travel time in the city and then to perform monetization analyses due to traffic disruption in the framework of WP3.

Figure 22: Flood hazard map for BAU scenario and return period of 10 years. Closed links are represented by red color, while links with limited velocity and no affected links are represented by orange and green colors respectively.

Figure 23: Flood hazard map for Adaptation 2 scenario and return period of 10 years. Closed links are represented by red color, while links with limited velocity and no affected links are represented by orange and green colors respectively.

2.5 Waste sector

In Barcelona there are a total of 27,134 waste containers, which can be classified either according to the fraction they contain (i.e. waste, organic, paper and cardboard, packaging (plastics), and glass), their volume in litres (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% (packaging), and 11% (glass). Regarding their loading, their distribution is as follows: 62% (lateral), 25% (bilateral), 12% (rear), and 1% (underground). All these containers have been studied in terms of their stability when exposed to urban floods according to the methodology explained in Deliverables 2.2 (Russo, 2018a) and 2.3 (Russo, 2019).

Stability functions for waste containers 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). 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) determine the shape of each function. The obtained stability thresholds were employed to analyse the potential behaviour of containers against floods in Barcelona caused by historical and low-return-period design storms (i.e. 1, 10 and 50 years). On the other hand, the Barcelona City Council has performed a GIS-based map with the location of all types of containers across Barcelona City. This information is essential in order to study if their current location may lead to a potential instability. A detailed description of this methodology can be found in a specific scientific paper about this issue (Martínez‐Gomariz *et al.*, 2019).

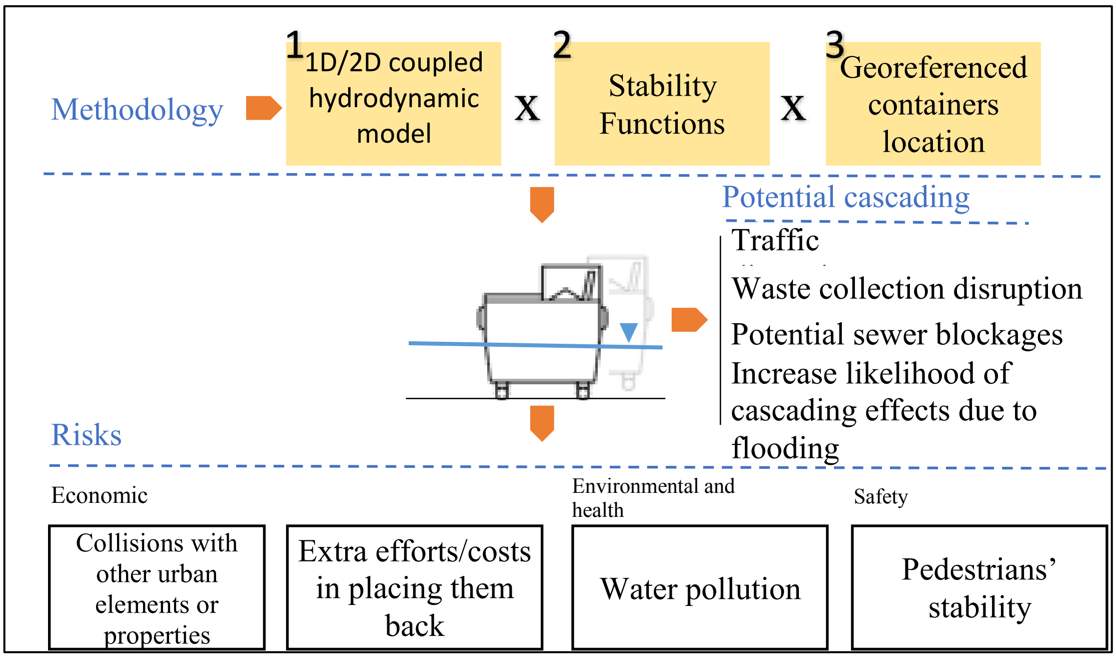


Figure 24. Methodology workflow and potential cascading effects and risks related to containers instabilities

2.5.1 Introduction and summary of climate hazards for the waste sector

In the previous Deliverables D2.2 and D2.3, once the methodology was proposed and described, the number of containers potentially unstable due to floods derived from design storms related to low-return periods were presented (Russo, 2018a) (Russo, 2019). Two scenarios were considered, present (Baseline) and future (BAU) rainfall conditions without the implementation of any adaptation measure. The expected increment of potentially unstable containers according to future rainfall conditions is presented in Figure 25 in absolute numbers and in Figure 26 by offering percentages values. These figures indicate that a high number of 873 containers is expected in case of a 50-year return period rainfall over the entire city and a containers-empty scenario. However, in terms of percentage the containers-full scenario is expected to increase the highest up to 36%.

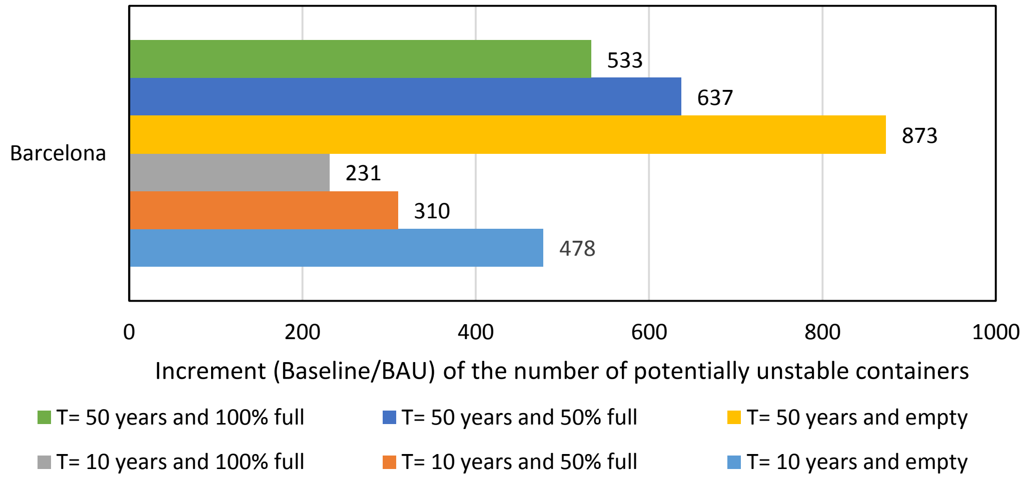


Figure 25. Increment (absolute numbers) of potentially unstable containers in Barcelona according to different fill levels and design storms.

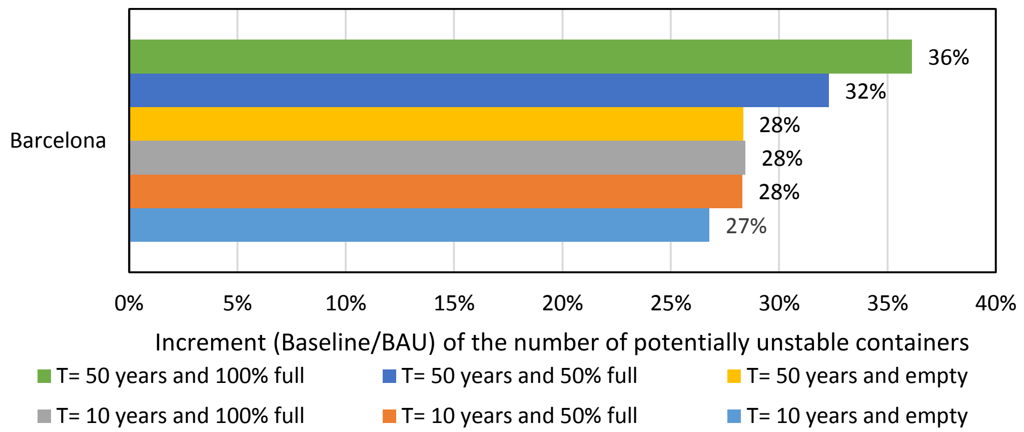


Figure 26. Increment (percentage) of potentially unstable containers in Barcelona according to different fill levels and design storms.

A detailed summary of increments per district is presented in Table 8, in which it can be observed that Eixample, Sants-Montjuic and Sant-Andreu are the more vulnerable districts in terms of containers instabilities.

Specific hazard maps have been developed showing the location of the containers with potential problems of instability. This kind of information can be used by the Municipality to decide different locations or to propose specific measures to guarantee the stability of these elements.

Table 8. Expected increase of containers potentially unstable per districts for BAU scenario

District	Containers			Containers potentially unstable (# (%)) according to considered scenarios								
				T = 1 years			T = 10 years			T = 50 years		
	Units	Units studied	Units flooded	0%	50%	100%	0%	50%	100%	0%	50%	100%
Ciutat Vella	1,147	624	460	0 0.00%	0 0.00%	0 0.00%	4 5.00%	7 10.77%	4 6.78%	25 27.17%	20 24.39%	16 21.62%
Eixample	4,864	4,808	2,845	0 0.00%	0 0.00%	0 0.00%	**87 18.24%**	**59 19.60%**	**49 22.48%**	**163 23.22%**	**103 22.29%**	**100 29.15%**
Sants-Montjuic	2,976	2,369	2,107	0 0.00%	0 0.00%	0 0.00%	**62 26.96%**	**71 51.45%**	**52 54.17%**	**191 39.71%**	**140 44.44%**	**115 49.57%**
Les Corts	1,648	1,602	1,499	0 0.00%	0 0.00%	0 0.00%	40 28.37%	25 39.68%	19 47.50%	49 21.88%	49 34.75%	40 42.55%
Sarrià-St. Gervasi	3,843	2,528	2,348	0 0.00%	0 0.00%	0 0.00%	67 39.41%	50 52.08%	30 41.67%	73 23.32%	50 24.04%	52 32.91%
Gràcia	2,135	1,246	801	0 0.00%	0 0.00%	0 0.00%	11 32.35%	4 13.33%	2 6.90%	21 36.21%	15 36.59%	13 36.11%
Horta-Guinardó	2,463	2,194	1,782	0 0.00%	0 0.00%	0 0.00%	16 23.88%	10 20.83%	5 11.90%	49 50.00%	23 32.86%	14 22.58%
Nou Barris	2,144	1,941	1,788	0 0.00%	0 0.00%	0 0.00%	39 26.00%	30 27.52%	24 26.09%	68 28.45%	54 30.17%	40 26.32%
St. Andreu	1,986	1,901	1,270	0 0.00%	0 0.00%	0 0.00%	**48 28.07%**	**22 23.40%**	**17 25.76%**	**61 19.12%**	**72 38.10%**	**54 41.22%**
St. Martí	3,928	3,928	2,936	0 0.00%	0 0.00%	0 0.00%	**104 39.39%**	**32 21.19%**	**29 29.59%**	**173 31.17%**	**111 38.95%**	**89 46.11%**

2.5.2 Adaptation strategies and measures and design criteria

A list of seven potential measures were proposed in D5.2 to form the strategy to adapt Barcelona against floods Table 9. Containers, as an essential part of the waste sector in Barcelona, have also been studied in detail because they are affected by floods in terms of stability. Therefore, a specific adaptation measure to guarantee the stability of containers during flood events is proposed here.

Table 9. Description of the pluvial floods strategy proposed for Barcelona

Strategy name	Description	Problem characterization	Potential measures forming the strategy
Flood impacts reduction in a context of climate change:	This strategy will be formed by a set of measures intended to reduce the impacts of flooding events identified for Barcelona in the framework of RESCCUE project. It includes structural measures, non-structural measures and nature-based solutions.	The morphology of Barcelona presents areas with high gradients (Collserola, Montjuïc) and flat areas near to the Mediterranean Sea. These characteristics, added to the typically heavy Mediterranean rainfalls with high intensities and short duration, leave the city in a prone situation to be flooded. Moreover, the land of the municipality was strongly urbanized during the last decades. All these aspects facilitate urban flash floods in several critical areas with significant economic damages and high hazard conditions for pedestrian and vehicular circulation and for the urban assets.	M1. Improvements of surface drainage system (New inlets) M2. Increase of sewer system capacity (I) (New pipes) M3.Increase of sewer system capacity (II) (New storage tanks for flooding protection) M4. SUDs (green roofs, infiltration trenches, detention basins for rural catchments) M5. Real Time Control Systems M6. Early Warning System M7. Self-healing algorithm implemented in the electrical distribution grid M8. Ensure the stability of waste containers

In 2016, fixation pieces (Figure 27) started to be installed in order to ensure the stability of containers when observed that only their own weight could cause their instability in steep streets. The number of installed pieces is 147 so far, but 574 more are planned to be installed in the short term. However, these pieces may be used also to ensure stability of containers located in flat or low-slope areas, which may be potentially unstable when an urban flood occurs. Therefore, these already-fixed containers are not potentially unstable due to floodwater and they have been removed from the analysed ones.

Figure 27. Fixation piece example, currently installed in 147 locations within Barcelona city.

In order to increase the resilience of waste sector against urban floods caused by a 10 years return period and future rainfall conditions in Barcelona, for an empty-containers scenario, 2,086 fixation pieces would be necessary to be installed. It has to be noted that a couple of pieces are needed to be installed per group of containers (Figure 27), thus two pieces have been taken into account per each group location where at least one potentially unstable container can be found. It would mean an estimated investment of 189,826 € (91€/piece). The purpose of these pieces will be to ensure the containers' stability due to floodwaters in flat areas, and due to their own weight in steep streets.

However, the adaptation measures proposed to reduce pluvial flood risks different from the ones derived from containers stability in Barcelona will reduce also the number of containers potentially unstable. Two of the different adaptation scenarios that have been implemented in the 1D/2D hydrodynamic model: 1) SUDS across the entire city, and 2) SUDS and structural measures across the entire city, have been considered here too. Moreover, the combination of these measures jointly with fixation pieces has been assessed in terms of reduction of number of unstable containers. Since the number of fixation pieces has been designed to avoid the containers displacement for 10-year return period and future rainfall conditions, lower return periods have not been assess as no container would move. The combination of adaptation scenarios is summarized in Table 10.

Table 10. Summary of adaptation scenarios considered in the Flood-Waste integrated model

ID	Adaptation scenario	T1			T10			T50		
		empty	50% filled	Full	empty	50% filled	Full	empty	50% filled	Full
S1	Fixation pieces for T10 BAU (M8)							✓	✓	✓
S2	SUDS (M4)				✓	✓	✓	✓	✓	✓
S3	SUDS + Structural (M4 + M1 + M2 + M3)				✓	✓	✓	✓	✓	✓
S4	SUDS and fixation pieces for T10 BAU (M4 + M8)							✓	✓	✓
S5	SUDS + Structural measures and fixation pieces for T10 BAU (M4 + M1 + M2 + M3 + M8)							✓	✓	✓

2.5.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

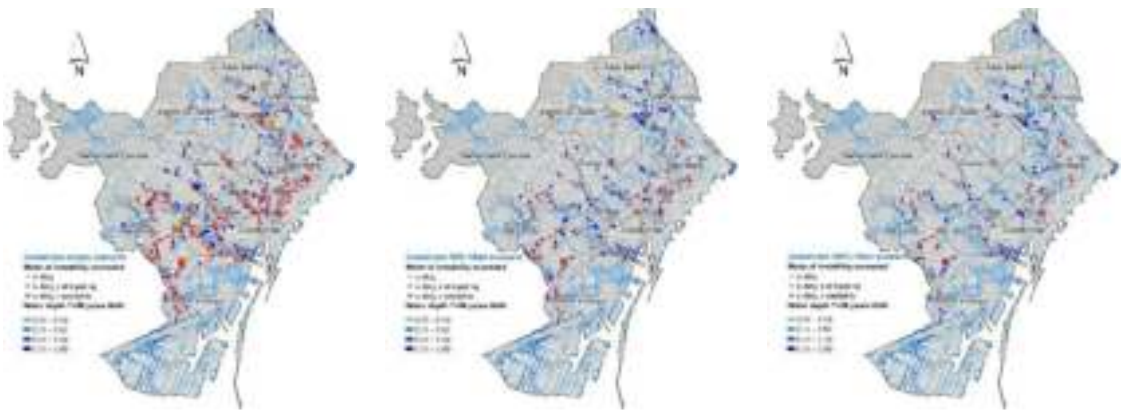
As a particular adaptation measure, the effect of the fixation pieces (S1) was firstly assessed for a 50-year return period design storm uniformly distributed across the entire city. The obtained results indicate that only 9% (empty), 4% (half) and 2% (full) of the studied containers would be potentially unstable in case a 50-year return period rain would fall over the entire city in a uniformly distributed manner.

The distribution of the potentially unstable containers among the Barcelona districts is provided in Table 11. 0% means empty containers, 50% means half full containers, while 100% means completely full containers.

Table 11. Containers potentially unstable after the implementation of fixation pieces (S1).

District	Containers			Containers potentially unstable (# (%)) according to considered scenarios		
				T = 50 years		
	Units	Units studied	Units flooded within the RESCCUE domain	0%	50%	100%
Ciutat Vella	1,147	624	460	33 7.17%	20 4.35%	11 2.39%
Eixample	4,864	4,808	2,845	**298** **10.47%**	**83** **2.92%**	**48** **1.69%**
Sants-Montjuic	2,976	2,369	2,107	**377** **17.89%**	**180** **8.54%**	**102** **4.84%**
Les Corts	1,648	1,602	1,499	88 5.87%	30 2.00%	15 1.00%
Sarrià-St. Gervasi	3,843	2,528	2,348	147 6.26%	52 2.21%	31 1.32%
Gràcia	2,135	1,246	801	34 4.24%	15 1.87%	11 1.37%
Horta-Guinardó	2,463	2,194	1,782	64 3.59%	21 1.18%	12 0.67%
Nou Barris	2,144	1,941	1,788	118 6.60%	48 2.68%	31 1.73%
St. Andreu	1,986	1,901	1,270	**156** **12.28%**	**73** **5.75%**	**45** **3.54%**
St. Martí	3,928	3,928	2,936	348 11.85%	105 3.58%	60 2.04%

Figure 28 shows the distribution of the expected unstable containers according to the three considered scenarios, empty, half and full containers, after the fixation pieces implementation and the simulation of 50 years return period.



Containers empty   Containers 50% filled   Containers full

Figure 28. Containers potentially unstable in case of a 50 years return period rainfall uniformly distributed across the entire city after implementing the fixation pieces (S1).

The other adaptation scenarios have also been assessed accordingly and the containers potentially stable under the different scenarios in terms of absolute numbers and percentage are presented in Table 12. As it can be observed, practically all containers are expected to remain stable with the implementation of S5. However, the results of the implementation of SUDS and fixation pieces (S3) in

Barcelona would produce a noticeable reduction of the containers' instabilities, even for the case of a 50-year return period storm.

Table 12. Summary of the results concerning the effects of the different adaptation scenarios

Adaptation Scenario	Containers	Containers potentially unstable (# (%)) according to considered scenarios					
		T = 10 years			T = 50 years		
	Units flooded within the RESCCUE domain	0%	50%	100%	0%	50%	100%
S1	17,836	0	0	0	1663	627	366
		0%	0%	0%	9%	4%	2%
S2		1550	974	693	3213	2097	1577
		9%	5%	4%	18%	12%	9%
S3		92	25	0	843	401	274
		1%	0%	0%	5%	2%	2%
S4		0	0	0	923	273	142
		0%	0%	0%	5%	2%	1%
S5		0	0	0	120	0	0
		0%	0%	0%	1%	0%	0%

All these instabilities have been computed also per districts as the following tables indicate.

Table 13. Containers potentially unstable after the implementation of the adaptation scenario S2.

Without fixation									
District	Containers			Containers potentially unstable (# (%)) according to considered scenarios					
				T = 10 years			T = 50 years		
	Units	Units studied	Units flooded within the RESCCUE domain	0%	50%	100%	0%	50%	100%
Ciutat Vella	1,147	624	460	49 10.65%	34 7.39%	32 6.96%	98 21.30%	82 17.83%	75 16.30%
Eixample	4,864	4,808	2,845	**410 14.41%**	**257 9.03%**	**172 6.05%**	**736 25.87%**	**469 16.49%**	**358 12.58%**
Sants-Montjuic	2,976	2,369	2,107	**208 9.87%**	**127 6.03%**	**94 4.46%**	**518 24.58%**	**335 15.90%**	**255 12.10%**
Les Corts	1,648	1,602	1,499	132 8.81%	61 4.07%	35 2.33%	244 16.28%	161 10.74%	107 7.14%
Sarrià-St. Gervasi	3,843	2,528	2,348	184 7.84%	112 4.77%	77 3.28%	342 14.57%	244 10.39%	186 7.92%
Gràcia	2,135	1,246	801	42 5.24%	32 4.00%	29 3.62%	73 9.11%	54 6.74%	45 5.62%
Horta-Guinardó	2,463	2,194	1,782	60 3.37%	46 2.58%	37 2.08%	121 6.79%	77 4.32%	63 3.54%
Nou Barris	2,144	1,941	1,788	142 7.94%	113 6.32%	88 4.92%	259 14.49%	193 10.79%	165 9.23%
St. Andreu	1,986	1,901	1,270	154 12.13%	84 6.61%	57 4.49%	**332 26.14%**	**206 16.22%**	**146 11.50%**
St. Martí	3,928	3,928	2,936	169 5.76%	108 3.68%	72 2.45%	**490 16.69%**	**276 9.40%**	**177 6.03%**

Table 14. Containers potentially unstable after the implementation of the adaptation scenario S4.

With fixation									
District	Containers			Containers potentially unstable (# (%)) according to considered scenarios					
				T = 10 years			T = 50 years		
	Units	Units studied	Units flooded within the RESCCUE domain	0%	50%	100%	0%	50%	100%
Ciutat Vella	1,147	624	460	0 0.00%	0 0.00%	0 0.00%	14 3.04%	2 0.43%	2 0.43%
Eixample	4,864	4,808	2,845	0 0.00%	0 0.00%	0 0.00%	**169 5.94%**	**33 1.16%**	**14 0.49%**
Sants-Montjuic	2,976	2,369	2,107	0 0.00%	0 0.00%	0 0.00%	**223 10.58%**	**67 3.18%**	**42 1.99%**
Les Corts	1,648	1,602	1,499	0 0.00%	0 0.00%	0 0.00%	59 3.94%	16 1.07%	6 0.40%
Sarrià-St. Gervasi	3,843	2,528	2,348	0 0.00%	0 0.00%	0 0.00%	103 4.39%	43 1.83%	22 0.94%
Gràcia	2,135	1,246	801	0 0.00%	0 0.00%	0 0.00%	28 3.50%	13 1.62%	7 0.87%
Horta-Guinardó	2,463	2,194	1,782	0 0.00%	0 0.00%	0 0.00%	39 2.19%	12 0.67%	6 0.34%
Nou Barris	2,144	1,941	1,788	0 0.00%	0 0.00%	0 0.00%	70 3.91%	27 1.51%	14 0.78%
St. Andreu	1,986	1,901	1,270	0 0.00%	0 0.00%	0 0.00%	**108 8.50%**	**40 3.15%**	**20 1.57%**
St. Martí	3,928	3,928	2,936	0 0.00%	0 0.00%	0 0.00%	110 3.75%	20 0.68%	9 0.31%

Table 15. Containers potentially unstable after the implementation of the adaptation scenario S3.

Without fixation									
District	Containers			Containers potentially unstable (# (%)) according to considered scenarios					
				T = 10 years			T = 50 years		
	Units	Units studied	Units flooded within the RESCCUE domain	0%	50%	100%	0%	50%	100%
Ciutat Vella	1,147	624	460	0 0.00%	0 0.00%	0 0.00%	9 1.96%	4 0.87%	3 0.65%
Eixample	4,864	4,808	2,845	**2 0.07%**	**0 0.00%**	**0 0.00%**	**176 6.19%**	**77 2.71%**	**46 1.62%**
Sants-Montjuic	2,976	2,369	2,107	42 1.99%	12 0.57%	0 0.00%	**170 8.07%**	**81 3.84%**	**56 2.66%**
Les Corts	1,648	1,602	1,499	0 0.00%	0 0.00%	0 0.00%	50 3.34%	12 0.80%	5 0.33%
Sarrià-St. Gervasi	3,843	2,528	2,348	**6 0.26%**	**1 0.04%**	**0 0.00%**	**120 5.11%**	**51 2.17%**	**33 1.41%**
Gràcia	2,135	1,246	801	0 0.00%	0 0.00%	0 0.00%	12 1.50%	6 0.75%	3 0.37%
Horta-Guinardó	2,463	2,194	1,782	11 0.62%	6 0.34%	0 0.00%	78 4.38%	46 2.58%	35 1.96%
Nou Barris	2,144	1,941	1,788	16 0.89%	4 0.22%	0 0.00%	97 5.43%	64 3.58%	55 3.08%
St. Andreu	1,986	1,901	1,270	6 0.47%	0 0.00%	0 0.00%	40 3.15%	19 1.50%	16 1.26%
St. Martí	3,928	3,928	2,936	9 0.31%	2 0.07%	0 0.00%	91 3.10%	41 1.40%	22 0.75%

Table 16 –Containers potentially unstable after the implementation of the adaptation scenario S3.

With fixation									
District	Containers			Containers potentially unstable (# (%)) according to considered scenarios					
				T = 10 years			T = 50 years		
	Units	Units studied	Units flooded within the RESCCUE domain	0%	50%	100%	0%	50%	100%
Ciutat Vella	1,147	624	460	0 0.00%	0 0.00%	0 0.00%	0 0.00%	0 0.00%	0 0.00%
Eixample	4,864	4,808	2,845	0 0.00%	0 0.00%	0 0.00%	19 0.67%	0 0.00%	0 0.00%
Sants-Montjuic	2,976	2,369	2,107	0 0.00%	0 0.00%	0 0.00%	**21** **1.00%**	0 0.00%	0 0.00%
Les Corts	1,648	1,602	1,499	0 0.00%	0 0.00%	0 0.00%	3 0.20%	0 0.00%	0 0.00%
Sarrià-St. Gervasi	3,843	2,528	2,348	0 0.00%	0 0.00%	0 0.00%	25 1.06%	0 0.00%	0 0.00%
Gràcia	2,135	1,246	801	0 0.00%	0 0.00%	0 0.00%	9 1.12%	0 0.00%	0 0.00%
Horta-Guinardó	2,463	2,194	1,782	0 0.00%	0 0.00%	0 0.00%	**27** **1.52%**	0 0.00%	0 0.00%
Nou Barris	2,144	1,941	1,788	0 0.00%	0 0.00%	0 0.00%	10 0.56%	0 0.00%	0 0.00%
St. Andreu	1,986	1,901	1,270	0 0.00%	0 0.00%	0 0.00%	0 0.00%	0 0.00%	0 0.00%
St. Martí	3,928	3,928	2,936	0 0.00%	0 0.00%	0 0.00%	6 0.20%	0 0.00%	0 0.00%

The analysis and discussion of the most vulnerable districts and the effectiveness of these adaptation scenarios in terms of reduction of number of containers potentially unstable are presented in D3.6.

2.6 Electrical sector

2.6.1 Introduction and summary of climate hazards for the electrical sector

In Barcelona, only the drainage flood model has been developed across all the city extent. This means that the sea-level rise or increases in the level of rivers have not been taken into account. Because of this, the distribution of the substations analysed in Deliverable 2.3 (placed in these areas) have not been assessed, avoiding in this way an underestimation of the potential hazards. However, the medium (MV) and high voltage (HV) substations are distributed across all the Barcelona municipality extent, and it is where the assessment has been focused on. Apart from that, the integrated flood-electrical model has been developed by following the steps explained in Deliverable 2.3 (Russo, 2019).

This part of the document is the summary of the results obtained from the integrated flood-electrical model considering different scenarios modelled by Aquatec. In this subsection the flooding hazards found for the electrical sector in the Baseline (BAS) and Business As Usual (BAU) scenario are presented, while in the following subsection the results found in this sector for the new models developed by Aquatec, considering the adaptation scenario to face with flooding problems, are explained.

Thus, there are two adaptation scenarios and outputs to be implemented and considered in the integrated flood-electrical model. In the first one, Sustainable Urban Drainage Systems (following SUDS) are applied, while the second one considers the combination of SUDS and Structural measures (following SiE).

Finally, in the last subsection of this chapter, a comparison between the BAU scenario with the cases of applying SUDS and SiE models are made, to see how flooding would affect the electrical substations by considering both sets of measures to implement in the drainage system, regarding the electrical sector.

The results presented in bar chart figures are categorised into three water depth levels which correspond to the failure probabilities given by the fragility curve presented in deliverable D3.4, section 2.5.3, also represented in Figure 29. The categories are explained below:

- **Neglected zone (0 cm to 10 cm).** This zone has been neglected on the assessment due to the very low probability of failure.
- **Category 1 (10 cm < WDA < = 80 cm)**. All substations affected within the range of 10 cm and 80 cm are counted. 80 cm corresponds to a failure probability of less than 3%. These are not counted in the next category.
- **Category 2 (80 cm < WDA < = 160 cm)**. All substations affected within the range of 80 cm and 160 cm are counted. 160 cm corresponds to a failure probability of 50%. These are not counted in the next category.
- **Category 3 (WDA >160 cm)**. All substations affected with 160 cm of water depth or more are counted.

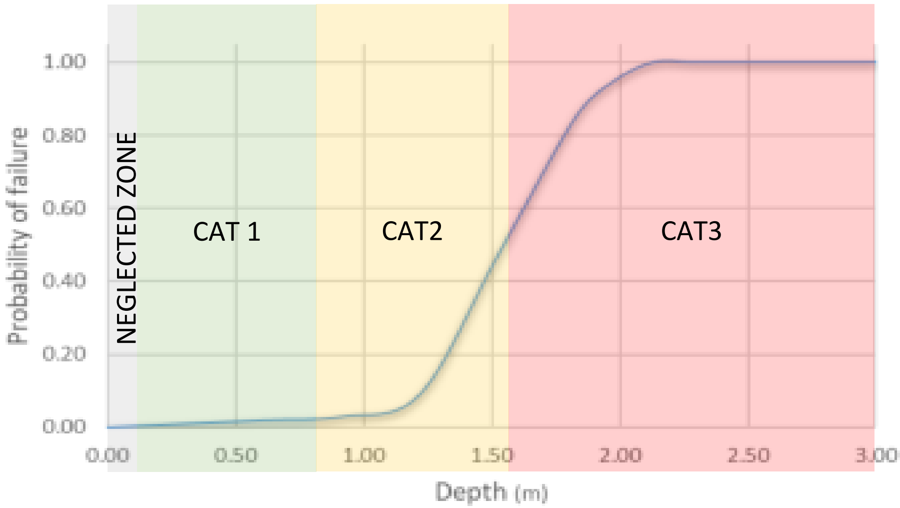


Figure 29.Explanation of the categorisation threshold provided, based on the fragility curve adapted from FEMA, 2009.

However, in the Barcelona electrical substations, only the first category has been reached.

Please consider that, the names of the substations affected are omitted due to confidential restrictions.

The results of the integrated flood electrical model applied to Baseline (following BAS) and Business as usual (following BAU) scenarios are given in this section. These scenarios have been assessed for all the locations provided and presented as stacked columns charts, but also in maps for the sake of clarity.

In Figure 30 the exposure of substations of different voltages (mostly MV substations) to flooding can be observed. There are no occurrences for return periods of T1 and it is in the return period T10 when two locations of each class (MV and HV) start to be affected in the BAS scenario, and one MV substation more in the BAU scenario. From T50 onwards, the number of MV substations exposed to flooding hazard increases up to nine in both scenarios, and up to three HV substations potentially affected in T500 in BAS and up to four in BAU (Figure 30 and Figure 31).

Hence, it has to be remarked the clear increase occurred from the baseline scenario to the business as usual scenario of substations exposed to flooding hazard.

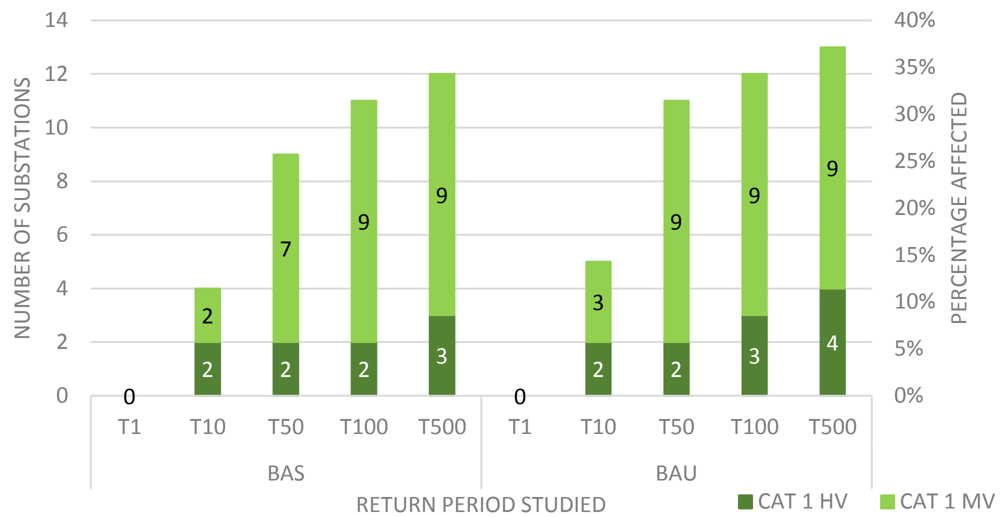


Figure 30. Number of substations affected in the BAS and BAU scenarios and their percentages over the total substations located in Barcelona.

Analysing Figure 31, it is clearly represented which substations present higher hazard respect to the others. In the baseline scenario, there are two substations exposed to flooding in the return period T10 (red colour dots) with affected area rates (AAR) of more than 40%, and 1 substation affected in return period T50 (Orange colour dots) with more than 80%.

However, in the BAU scenario, an increase in the AAR up to a 60% is produced in one of the substations, which in the BAS scenario was affected with an AAR of 20% Figure 311.

For a better understanding of Figure 31, it has to be remarked that the substations affected in a certain return period, are also affected in a higher return period, but they are overlapped by the shown return period because both of them present the same size and consequently the same or very similar AAR.

Figure 31. Representation of the different substations affected in BAS and BAU scenarios, for the different return periods analysed and taking into account the Affected Area Rate (0-100%).

2.6.2 Adaptation strategies, measures and design criteria

The assessment of the flood hazard reduction for the electrical system in Barcelona has been performed according to the two adaptation scenarios (SUD and SiE) and following the same methodology and criteria adopted for the Baseline and BAU scenarios.

In Figure 32 the numerical results of the sites potentially affected by floods after applying the prevention measures contained in the SUD and SiE models are summarised. For SUD adaptation scenario, 4 substations appear to be potentially affected by flooding in T10 (2 MV and 2 HV), 10 substations in T50 (8MV and 2 HV), 11 substations in T100 (9MV and 2 HV) and 13 in the return period T500 (9 MV and 4 HV). This means that in the worst case, 37% of the Barcelona substations would be exposed to flooding.

However, when the combination of SUDS measures and structural measures are applied (SiE), only one HV substation is exposed, while only 5 MV substations are exposed when a T500 flooding event occurs. Thus, the worst case would be during a T500 flooding event where 18% of the Barcelona substations would be exposed.

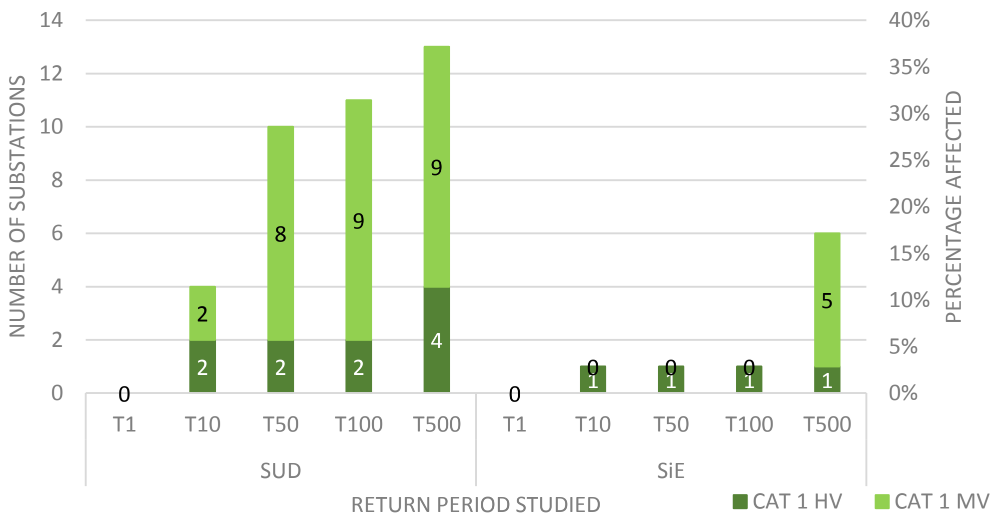


Figure 32. Number of substations affected in the SUD and SiE scenarios and their percentages over the total substations located in Barcelona.

Looking at the maps depicted in Figure 33, in the case of applying the SUD measures there would be two substations affected in T10 and another two in T50 with maximum AAR of 60%.

For extreme cases when the application of SUD and SiE scenarios are not enough to prevent the water penetration into the substations, also could be designed other measures that have not been considered in this study, as would be the establishment of flood defences, the use of elevated substations, the application of hydrophobic coatings to substations' inner elements, or even the implementation of extraction water pumps inside the substation to evacuate water in case of flooding (Jufri, Kim and Jung, 2017).

Figure 33. Representation of the different substations affected after applying SUD and SiE measures to BAU scenario, for the different return periods analysed and taking into account the Affected Area Rate (0-100%).

2.6.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

Figure 34 presents the comparison among BAU scenario, and SUD and SiE adaptation scenarios once measures are applied.

To represent the effectiveness of the considered measures, the results are expressed in terms of reduction of the number of affected sites after applying adaptation measures, and in terms of reduction percentage over the total number of substations. Hence, when SUDS are applied, it is shown how one substation is taken out from the flooding risk. However, looking at Figure 35, it is possible to see how the reduction of AAR achieved is less than 20%. Therefore, it can be affirmed that SUDS measures are not very effective concerning the electrical sector. In Figure 36 it is also shown how the AAR reduction achieved for all the return periods is about 10%.

However, the effectiveness increases considerably when structural measures are also applied (SiE). Figure 34 shows how the number of affected substations is reduced in 4 for T10, 10 for T50, 11 for T100 and 7 for T500, reducing in the best case up to a 47% considering both types of substations (MV and HV). Also, when looking at Figure 35, it is observed also a great reduction of the AAR, which decreases up to 60% for T10, and up to 80% in T50. When averages are taken into account, it is possible to see an average reduction of the AAR affected by around 30% and from 5 to 7 cm of water depth less (WDA) (Figure 36).

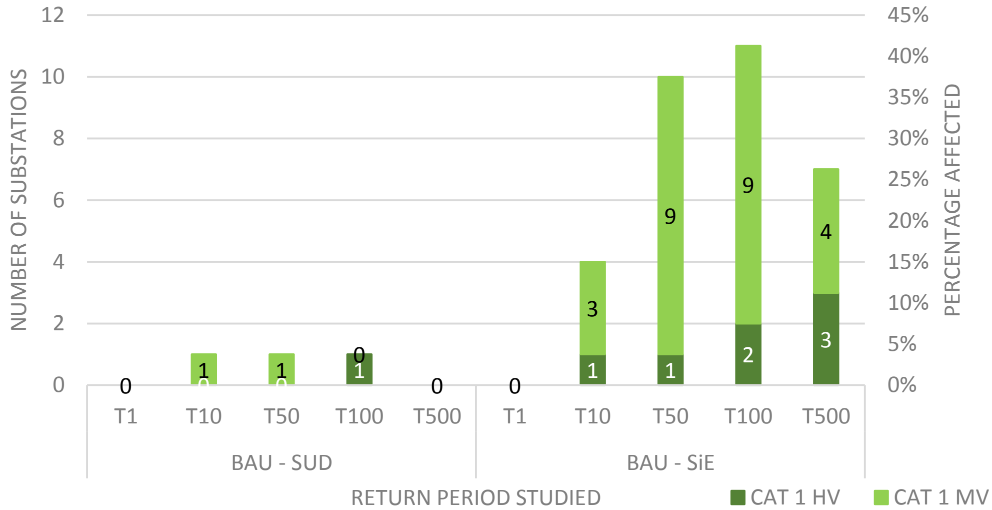


Figure 34. Comparison of BAU scenario with BAU and SiE, showing the number of substations that are OUT of hazard in BAU scenario by applying the different sets of prevention measures, and the percentage of reduction achieved.

Figure 35. Representation of the substations where the Affected Area Rate was reduced after applying SUD and SiE measures to BAU scenario for the different return period analysed and taking into account the Affected Area Rate (0-100%).

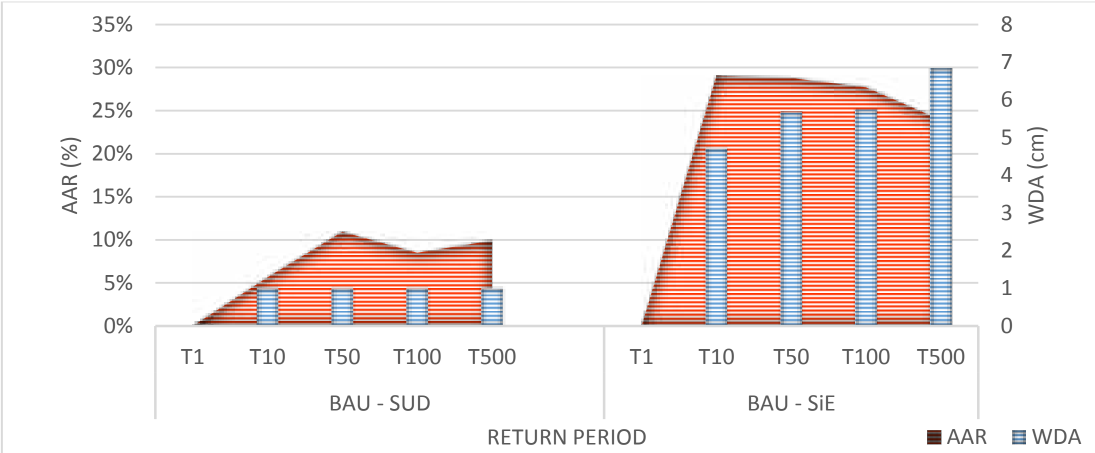


Figure 36. Average of reduction of the Affected Area Rate and Water Depth Average achieved by applying the different sets of prevention measures (SUD and SiE) for each return period analysed.

2.7 Beach sector

2.7.1 Introduction and summary of climate hazards for beach sector

This chapter evaluates the health hazard and risk for people bathing in poor sea water quality and also the impacts that Combined Sewer Overflows (CSOs) have on the receiving water body. Poor bathing sea water quality is often caused by CSOs that occur during rainfall events when the urban drainage system cannot handle all the combined sewer water and therefore it discharges untreated sewer flow to the sea of Barcelona. This poses a health hazard and risk for bathing people. The impact of climate change on health risk is also analyzed and finally adaptation measures are proposed and evaluated based on their capacity of reducing selected key performance indicators including hazards and risks.

The methodology, the model description and calibration of the sea water quality model for hazard assessment was explained in Deliverable 2.2 (Russo, 2018a). In this chapter, the sea water model was used to assess the impacts of 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 that is one of the two mandatory parameters of the Bathing Water Directive (BWD 2006/7/CE (European Parliament, 2006).

The marine model is 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 calibrate and validate the model (Russo, 2018a). The model was then used to simulate hazard maps for people bathing in the sea.

In Barcelona, every summer, several (usually less than 10) CSOs events occur and 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 CSO structures located along the beaches of Barcelona. Figure 37 shows an example of a sea water quality simulation after a CSO event.

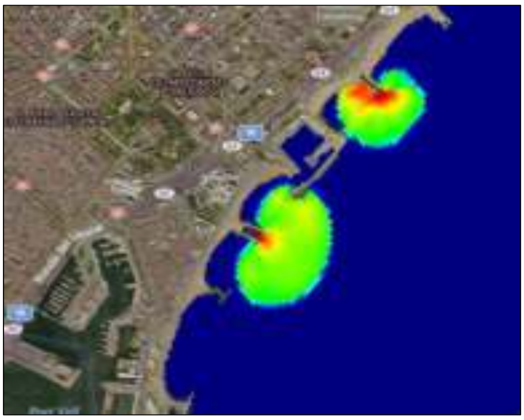


Figure 37: Sea water quality simulation after a CSO event in Barcelona (Red=high; Blue=low E.Coli concentrations in sea water).

Figure 38 shows the time duration of high hazard per bathing season at different beaches of Barcelona for the Baseline and BAU scenario. The BAU is assumed to be the same as the baseline scenarios since the analyzed future rainfall in Barcelona was analyzed and it would not increase the annual number and annual volume of CSOs in the future (Russo, 2019) (The future rainfall time series has similar annual volumes and number of events compared to past rainfall).

The CSO volume produced every year and the quantification of pollutants discharged by CSOs is shown in the following result section.

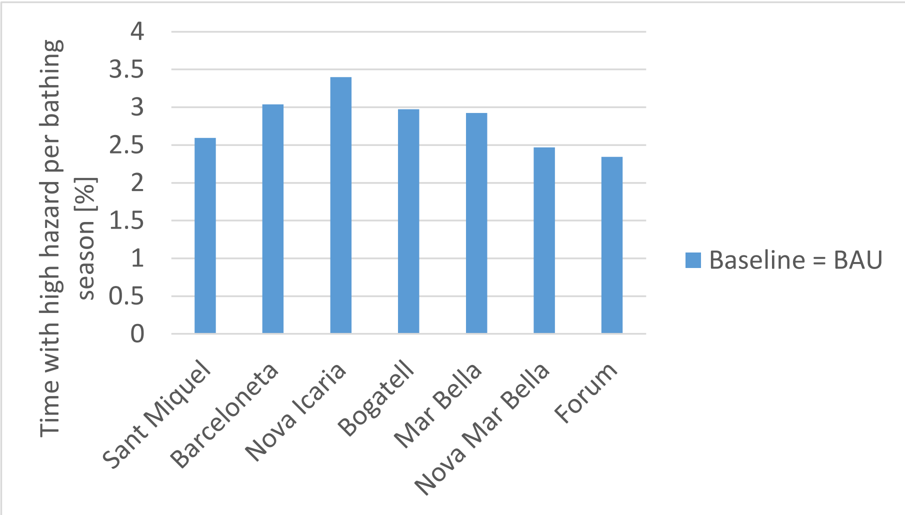


Figure 38. Time duration of high hazard per bathing season (25th of may. – 15th of sep.) at different beaches of Barcelona.

2.7.2 Adaptation strategies, measures and design criteria

Two different adaptation scenarios are considered for reducing the impacts on the receiving water bodies:

- SUDS. This scenarios proposes and analyses the implementation of SUDS.
- SUDS and detention tanks. This scenario assumes the implementation of SUDS and structural detention tanks.

SUDS scenario

The Technical Plan for the exploitation of alternative water resources of Barcelona (Pla Tècnic per l'Aprofitament de recursos Hídrics Alternatius de Barcelona, PLARHAB) promotes the exploitation of rain water through the implementation of Sustainable Urban Drainage Systems (SUDS). Such systems can reduce stormwater runoff volume and intensities and therefore reduce CSOs. Figure 39 shows the location of all the SUDS considered in Barcelona. The colored lines corresponds to the infiltration trenches planned on the streets of Barcelona and the blue triangles all the detention/retention ponds in the areas upstream of the city drainage network. Green roofs are not shown.

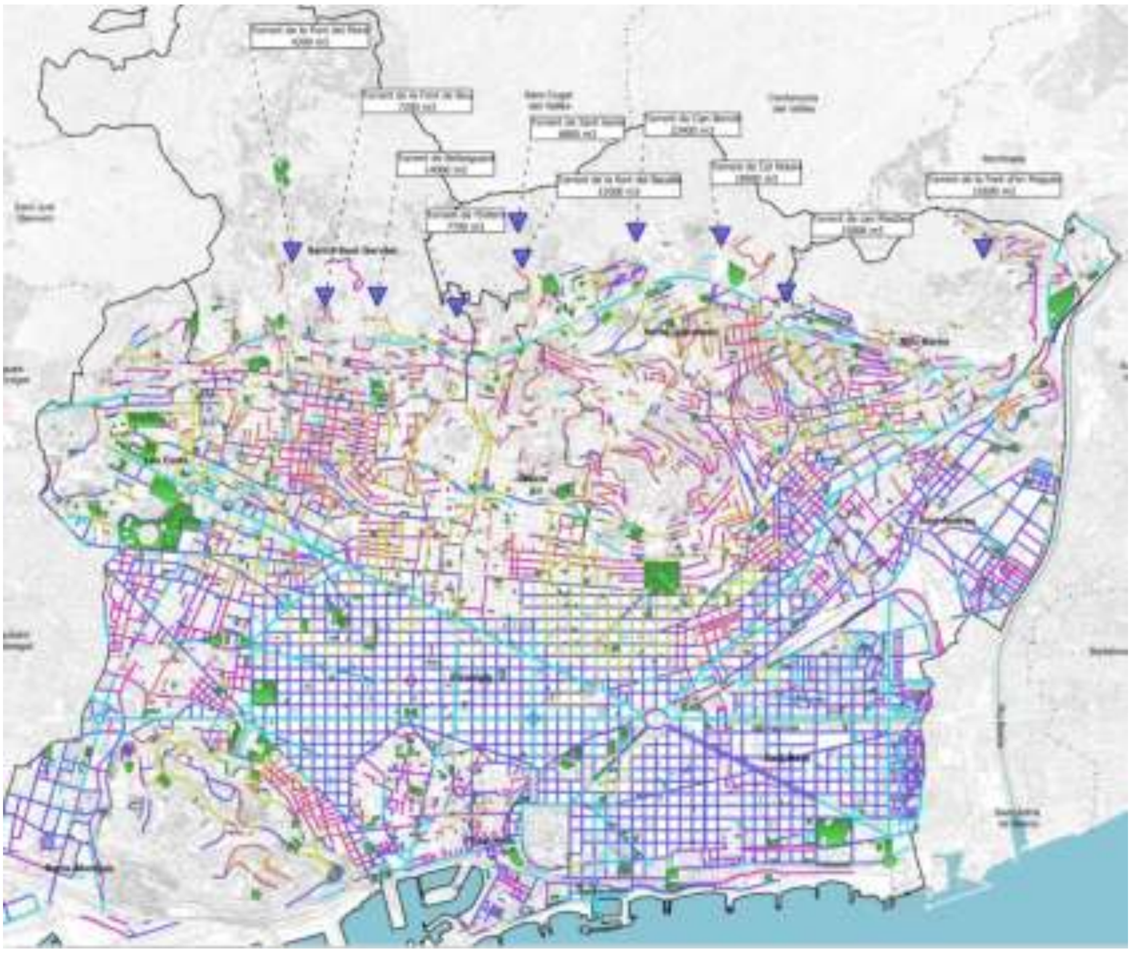


Figure 39. Map of the SUDS proposed in Barcelona.

There are 3 different types of SUDS considered as part of this scenario:

- Infiltration trenches: these are described in the PLARHAB. These trenches are devised to collect stormwater runoff from sidewalks and partly also from the road lanes. Figure 40 shows an example of one of the five different types proposed. The five different types proposed depend on the slope and the width of the road:
    - Type 1.1: For road between 9 and 15 m width and between 0 and 2.5 % slope
    - Type 1.2: For road between 9 and 15 m width and between 2.5 and 6 % slope
    - Type 2.3: For road between 15 and 40 m width and between 0 and 2.5 % slope
    - Type 4: For road between 15 and 40 m width and between 2.5 and 6 % slope
    - Type 5: For road of more than 40 m width and between 0 and 2.5 % slope

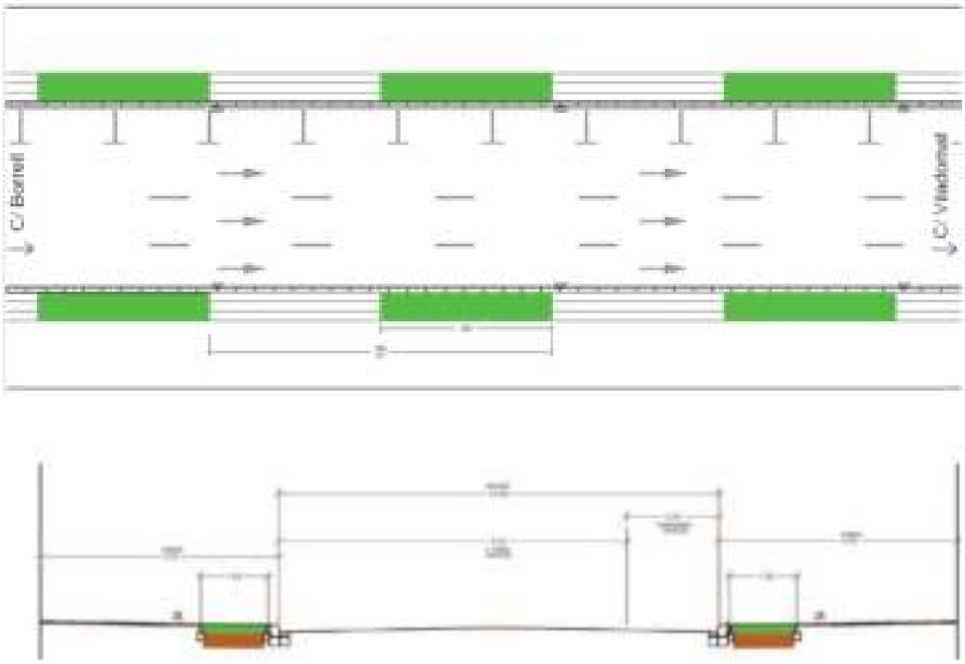


Figure 40. Example of SUDS of type 1.2.

- Detention/retention ponds (or basins). These systems are called Detention/retention ponds as their objective is to detain temporarily the stormwater runoff in order to reduce peak flows and also to retain part of the water that can be used for other purposes such as irrigation. These kind of SUDS are proposed in the PLARHAB. These systems are dimensioned as part of this study. These systems are designed to detain all the excess stormwater runoff generated by a 10 year event on the rural green areas surrounding Barcelona that drain into the downstream drainage network of the city (Table 17).

Table 17. Volumes of the retention/detention ponds.

Code	Stream name	Area of the catchment [ha]	Volume of the system (m3)
33	Torrent de can MasDeu	69.8	15800
24	Torrent de Can Borrell	84.54	23400
43	Torrent de la font del Bacallà	60.97	15500
22	Torrent de Cal Notari	69.6	18500
49	Torrent de la Font d'en Magués	51.87	15600
19-20-21	Torrent de Bellesguard	36.05	14000
46-47	Torrent de la Font de Bou	23.91	7200
62	Torrent de l'Infern	25.77	7700
54	Torrent de la Font del Mont	12.3	4200
77-78	Torrent de Sant Genís	18.65	6800

- Green roofs. Extensive green roofs are proposed similarly to the study *Cobertes i Murs Verds a Barcelona* that was developed within the CORFU EU project (Donna Sto. Domingo *et al.*, 2014).

SUDS and detention tanks scenario

In this scenario the SUDS proposed in the previous sections and new detention tanks will be implemented (Table 18). These tanks were proposed in the previous master drainage plan of Barcelona (PICBA06), so 15 new detention tanks with a total volume of 525 500 m^3 are proposed (Table 18).

Table 18. Detention tanks proposed.

Name of the tank	Catchment	Volume (m^3)	
		Barcelona	**Out of Barcelona**
Bac de Roda	Bac de Roda	80.000 m^3	
Bogatell	Bogatell	80.000 m^3	
Ciutadella-Barceloneta	Ribera	90.000 m^3	
Port Vell – Colon	Port Vell	15.000 m^3	
Port Vell-Passeig Montjuic	Port Vell	7.500 m^3	
Cementiri Montjuic	Cementiri Montjuic	5.000 m^3	
Motors	Zona Franca	72.000 m^3	
Amadeu Torner	Amadeu Torner		22.000 m^3
Seat	Seat		16.000 m^3
ZAL	Carrer 6		32.000 m^3
Vallbona	Vallbona	2.000 m^3	
Torrent Tapioles-Torre Baró	Torrent Tapioles-Torre Baró	30.000 m^3	
Interceptor Estadella	Interceptor Estadella	23.000 m^3	
Torrent Estadella-Bon Pastor	Torrent Estadella-Bon Pastor	41.000 m^3	
Guipúscoa-Alarcón	Guipúscoa-Alarcón		10.000 m^3
		445.500 m^3	80.000 m^3
		525.500 m^3	

2.7.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

The 2 adaptation measures scenarios presented in the previous section ("SUDS" and "SUDS and detention tanks" scenarios) are simulated in order to evaluate their impacts based on the following key performance indicators. This section shows how the different adaptation measures were simulated.

Modelling of infiltration trenches

Infiltration trenches are simulated in the urban drainage model using the Horton model. The rationale is that trenches have a storage and infiltration capacity. During peak stormwater runoff the storage would fill and during dry periods the infiltration into the soil would recover the storage capacity. In this case the Horton model (that was conceived only for infiltration) was used to reproduce several hydrological processes associated to these infiltration trenches: stormwater runoff from the area connected to the trench, storage within the trench volume and infiltration into the soil. For this reason, the selected Horton parameters are meant not to reproduce only a specific soil type infiltration but are meant to reproduce the 3 hydrological processes mentioned. Generally, high infiltration capacity should be associated to the trenches because of the storage capacity that allow longer infiltration periods after rainfall events. For instance it can take several hours or days to empty such systems depending on the local infiltration capacity. The following model parameters are applied to the infiltration trenches:

- Initial loss: 0.28 mm
- Horton parameters:
  - Initial infiltration rate: 100 mm/h
  - Final infiltration rate: 37 mm/h
  - Capacity decrease exponent: 4.14 h^{-1}
  - Capacity increase exponent (recovery): 0.036 h^{-1}

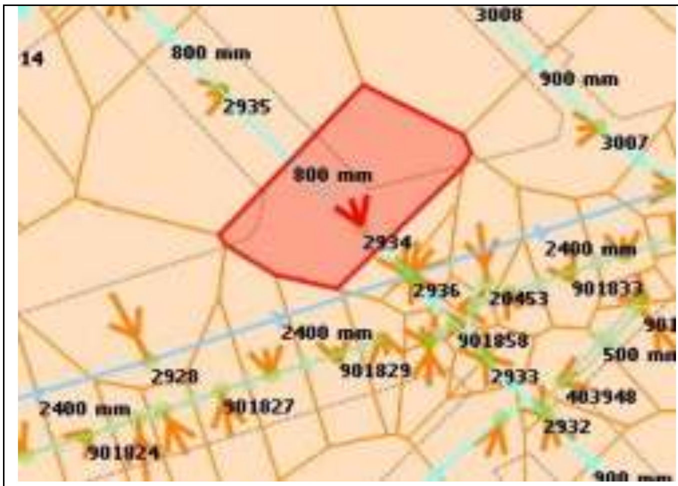
The excess stormwater runoff contributes to the selected SWMM rainfall-runoff model that is included into Infoworks ICM (SWMM rainfall-runoff model is a selectable option within the Infowork interface). Figure 41 shows all the model parameters used.

Propiedades de la Superficie de Escorrentía			
Superficie de Escorrentía ID	31		SUDS
Descripción	SUDS		SUDS
Tipo de Superficie	Pervious		SUDS
Tipo de Tránsito de Escorrentía	Abs		SUDS
Valor del Tránsito de Escorrentí	0.200		SUDS
Pendiente del Terreno (m/m)	0.000000		SUDS
Tipo de Volumen de Escorrentía	Horton		SUDS
Tasa de Infiltración Inicial Horto	100.000		SUDS
Tasa de Infiltración Final Hortor	37.000		SUDS
Constante de Decaimiento de H	4.140		SUDS
Porosidad Inicial para Pérdida	1.000		
Tipo de Pérdida Inicial	Abs		SUDS
Valor de la Pérdida Inicial (m)	0.00028000		SUDS
Constante de Recuperacion de I	0.036		SUDS
Modelo de Tránsito	SWMM		SUDS

Figure 41. Model parameters used for the simulation of infiltration trenches, in Spanish.

Because the proposed infiltration trenches should be constructed into existing impervious areas and because such trenches collect stormwater runoff from a larger area compared to their construction area, the impervious area of the 1D model sub catchments is modified accordingly. The green roof area is approximately 143 ha and the infiltration trench 181 ha (note that the trenches receive stormwater runoff from a larger area).

Based on a GIS analysis of the 5 different types of infiltration trenches together with the simulated impervious road areas, it was estimated that the proposed infiltration trenches have a catchment area 6-10 times larger compared to their construction area. The Horton model with the above mentioned parameters was applied to both the construction area of the infiltration trenches and also their catchment areas. Figure 42 shows an example of how the type of drainage area was changed from impervious to pervious in order to simulate infiltration trenches. Figure 42 shows an urban catchment that has in the baseline scenario has a 95% of the area that is impervious due to roofs and roads and a 5% area that is green due to some green spaces. It is shown that in the SUDS scenario the impervious area (Area 1) is reduced to 57.8% to live space to a 37.2% of SUDS area (Area 3).



Baseline scenario:

Superficies como porcentaje	
Área de Escorrentía 1 (%)	95.000
Área de Escorrentía 2 (%)	5.000
Área de Escorrentía 3 (%)	0.000
Área de Escorrentía 4 (%)	0.000

SUDS scenario:

Superficies como porcentaje	
Área de Escorrentía 1 (%)	57.790
Área de Escorrentía 2 (%)	5.000
Área de Escorrentía 3 (%)	37.210
Área de Escorrentía 4 (%)	0.000

Figure 42. Example showing of how the drainage area was changed from the baseline to the SUDS scenario in order to simulate infiltration trenches.

Modelling of the retention/detention ponds

The retention/detention ponds are simulated as storage nodes in the urban drainage model. Such nodes receive the stormwater runoff from the corresponding rural sub catchment as shown in Figure 43. The volume of each of the 10 tanks was provided in Table 17. Each pond has a drainage pipe of 100 mm diameter that is connected to the sewer network so that part of the water is returned to the network and part of the water is extracted from the model for other uses such as irrigation. So the function of these ponds is not only the flood reduction of the downstream catchments but also the storage of stormwater volume for other uses. That is why the operation of these ponds is not focused on the peak flow reduction, but only to store the maximum runoff.

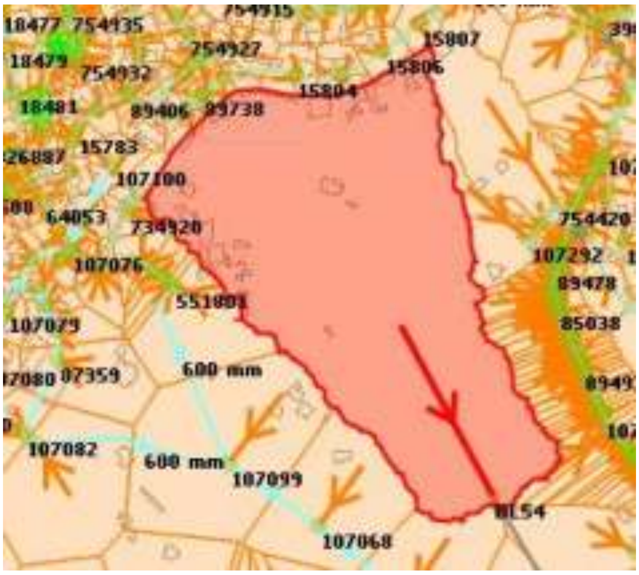


Figure 43. Example of the modelling the stream Font del Mont.

The volumes of such ponds were estimated to accommodate all the stormwater runoff from a 10 year design storm. The excess water generated by higher return period events would generate surface runoff (Figure 44).

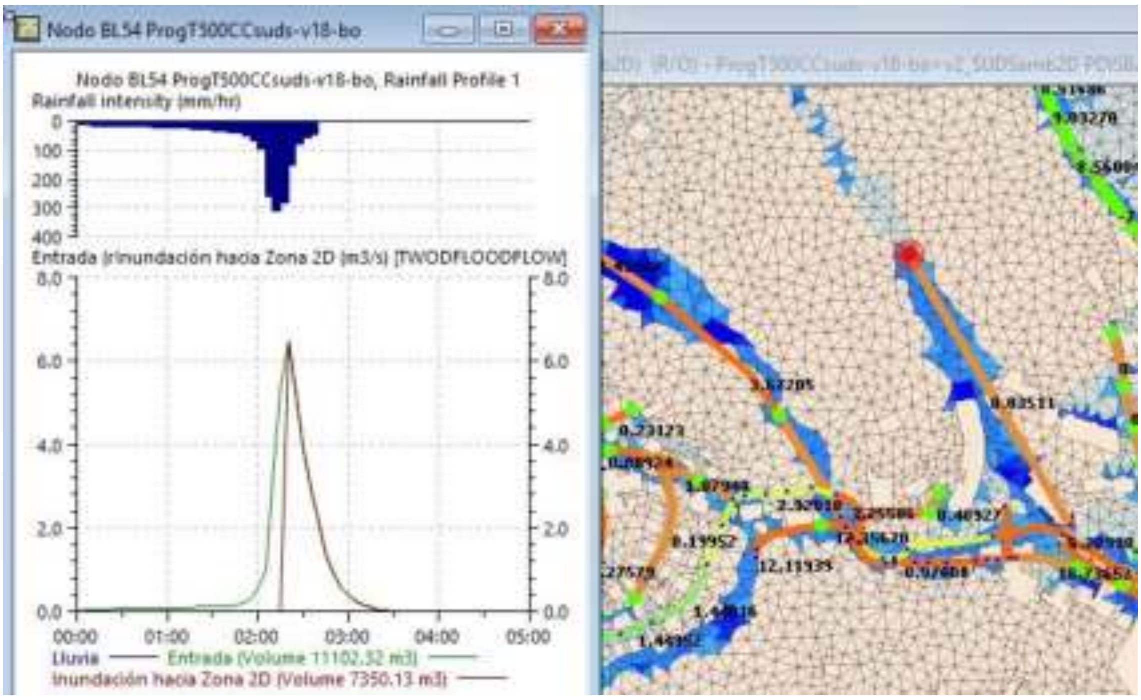


Figure 44. Example of the results of the modelling of the pond 54 for a design storm of 500 years. Once the pond is full it generates flooding.

Modelling of green roofs

Green roofs are simulated using the Horton model. Similar model parameters to green areas are applied except for the final infiltration rate that is set to 0 mm/h. This is because once the porous media of an extensive green roof is fully saturated the reduction capacity of stormwater runoff of design storms is assumed to be limited (Locatelli *et al.*, 2014).

Propiedades de la Superficie de Escorrentía	
Superficie de Escorrentía ID	32
Descripción	Teulades verdes
Tipo de Superficie	Pervious
Tipo de Tránsito de Escorrentía	Abs
Valor del Tránsito de Escorrentía	0.200
Pendiente del Terreno (m/m)	0.000000
Tipo de Volumen de Escorrentía	Horton
Tasa de Infiltración Inicial Horton (mm	76.000
Tasa de Infiltración Final Horton (mm/l	0.000
Constante de Decaimiento de Horton	4.140
Porosidad Inicial para Pérdida	1.000
Tipo de Pérdida Inicial	Abs
Valor de la Pérdida Inicial (m)	0.00028000
Constante de Recuperacion de Hortor	0.036
Modelo de Tránsito	SWMM

Figure 45. Model parameters for the proposed extensive green roofs, in Spanish.

Modelling of the detention tanks

The detention tanks are simulated as storage nodes in the urban drainage model. Such tanks are located close to the CSO points and are meant to receive CSO flows. During wet periods, the CSO flow accumulates into the tank and if the capacity of the tank is exceeded CSO to the receiving water body occurs. During dry period a pump empty each tank returning the combined sewer to the system so that it can be treated. The pumping rate was calculated so that each tank would empty in a day and a half.

2.7.4 Results of the simulations of adaptation strategies and measures to achieve hazard and risk reduction

This section present the results of a whole year continuous simulation of the coupled urban drainage and sea water quality model.

The results of the sea water quality simulation of a bathing season (25th of May – 15th of September) provide the duration of insufficient bathing water quality that corresponds to sea water E.Coli concentrations > 500 CFU/100ml. This duration indicates the time with high hazard for bathing people and since we are analyzing only the bathing season with high people exposure and vulnerability it corresponds also with the duration of the period with high risk for people. Table 19 shows the simulated duration of insufficient bathing water quality at all the beaches of Barcelona. Figure 46 shows the results in a graphical form. The baseline, that in this case coincides with the BAU scenario results, shows average time of 2.82% meaning that during this selected representative bathing season, there are 3.22 days with insufficient bathing water quality caused by CSOs. The variation among the different beaches is in the range from 2.35% at Forum up to 3.40% at Nova Icaria. The SUDS scenario results show that SUDS can reduce the duration to 2.36 % and SUDS and detention tanks to 1.80 %. Despite these results are strictly related to the rainfall registered during this selected representative simulation year (2009), the simulation results provided useful values to quantify the performance of the different scenarios.

Table 19. Simulated time with insufficient bathing water quality during the bathing season (25th of May – 15th of September) as a function of the different scenarios.

		Beach name							
	Pollution time	Sant Miquel	Barce-loneta	Nova Icaria	Bogatell	Mar Bella	Nova Mar Bella	Forum	MEAN
Baseline = BAU	Days / bathing season	2.96	3.47	3.88	3.39	3.33	2.81	2.67	3.22
	percentage %	2.60	3.04	3.40	2.97	2.92	2.47	2.35	2.82
SUDS	Days / bathing season	2.56	3.26	2.86	2.67	2.11	2.73	2.62	2.69
	percentage %	2.25	2.86	2.51	2.35	1.85	2.39	2.30	2.36
SUDS and detention tanks	Days / bathing season	1.44	1.61	2.53	2.28	1.94	1.95	2.58	2.05
	percentage %	1.26	1.41	2.22	2.00	1.70	1.71	2.26	1.80

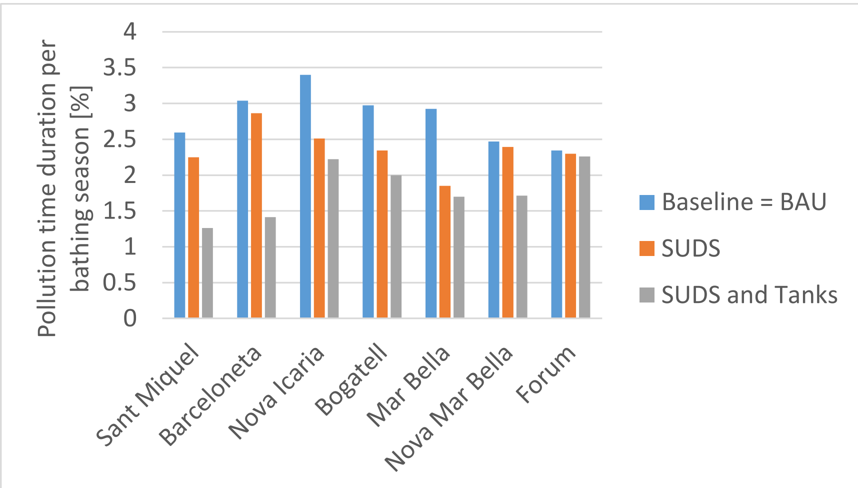


Figure 46. Results of the baseline, SUDS and SUDS and detention tanks scenario. Percentage of time during a bathing season with insufficient bathing water quality according to the BWD.

The results are also sensitive to the definition of the duration of a bathing season. Table 20 shows that the selected bathing season (25th of May – 15th of September) provides a kind of values that are in between the ones provided by the other 2 bathing season definitions.

Table 20. Model sensitivity to different definitions of duration of a bathing season.

	Definition of bathing season		
	25 May - 15 Sep	25 May - 14 Sep	1 Jun - 30 Sep
Baseline = BAU	2.82	1.97	4.68
SUDS	2.36	1.52	3.85
SUDS + Tanks	1.80	1.30	2.92

The impacts of CSOs on the receiving water bodies of Barcelona were also quantified in terms of annual CSO volume and discharged (concentration and total mass) of Suspended Solids, Biological Oxygen Demand and ammonium. Three different receiving water bodies were distinguished: the harbor, the beaches and the Besòs River.

Suspended Solids, Biological Oxygen Demand and ammonium discharged are calculated as a function of the CSO volume. Table 21 shows the reference concentrations applied according to the Spanish Manual for the construction of detention tanks for CSOs (Barro *et al.*, 2014). If the CSO volume comes directly from the combined sewer system the concentrations are higher compared to a CSO that comes from a detention tank. Detention tanks reduce contaminants mainly due to the settling of suspended solids that are retained in the tank.

Table 21. Concentrations used to compute SS, BOD_5, and NH_4^+ as a function of the CSO volume.

Concentration	In the sewer system	At the outlet of a detention tank
SS [mg/L]	324	121
DBO_5 [mg/L]	196	78
NH_4^+ [mg/L]	9	5.4

Table 22 shows the results for the different adaptation scenarios. SUDS scenario reduces CSO volume by 38 % and SUDS and detention tanks together by 52 %. SS, BOD5 and NH4+ are also significantly reduced.

The SUDS scenario is characterized by a widespread implementation of infiltration trenches. The simulation of infiltration trenches at such large scale is highly uncertain due to lack of local soil infiltration capacity data, final design criteria that will be used to dimension the trenches and also whether the trenches can or cannot infiltrate stormwater runoff due to potential local regulation that might not allow stormwater runoff infiltration because of potential pollution problems or affection to existing buildings. (Locatelli *et al.*, 2015).

Table 22. CSO volume, Suspended Solids, Biological Oxygen Demand and ammonium discharged in the different events.

Scenario	CSO	V (m3/any)	SS (kg/any)	BOD5 (kg/any)	NH4+ (kg/any)
Baseline = BAU	Harbour	8 587 651	2 782 399	1 683 180	77 289
	Beaches	9 015 253	2 920 942	1 766 989	81 137
	River	1 347 125	436 469	264 037	12 124
	Total	**18 950 029**	**6 139 809**	**3 714 206**	**170 550**
SUDS	Harbour	6 988 145	2 264 159	1 369 676	62 893
	Beaches	5 661 510	1 834 329	1 109 656	50 954
	River	1 040 287	337 053	203 896	9 363
	Total	**13 689 942**	**4 435 541**	**2 683 229**	**123 209**
SUDS and detention tanks	Harbour	5 378 821	907 294	568 621	33 594
	Beaches	3 114 638	766 427	469 383	23 727
	River	570 025	128 367	78 987	4 131
	Total	**9 063 484**	**1 802 088**	**1 116 991**	**61 452**

2.8 Barcelona surface water resources: Drought model

2.8.1 Introduction and summary of climate hazards for the water resources sector on Barcelona city

Water supply in Barcelona is warranted by the water resources of the Llobregat's and Ter's basins. Both watersheds have the upper part to manage water, which facilitates to modulate the required water resources.

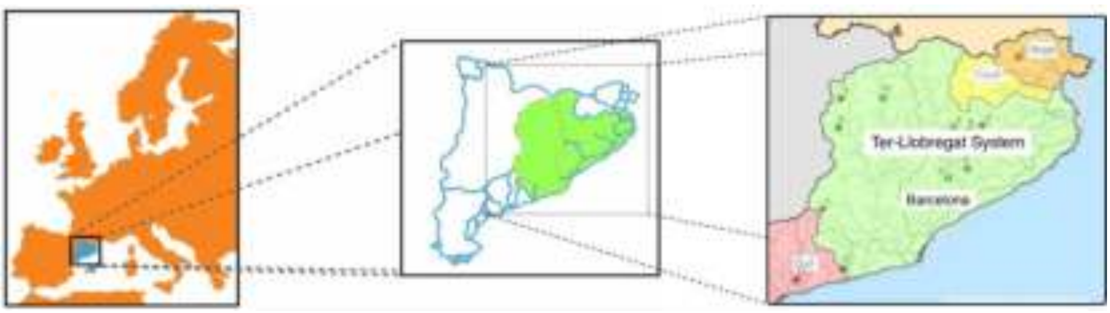


Figure 47: Location of the Ter-Llobregat reservoir system, concerning Barcelona city.

Barcelona's city is placed far away from these reservoirs, but the water scarcity state basically depends on the stored water volumes on that reservoir system. When those volumes are lower than some specific levels settled by the Drought Plan developed by the Catalan Water Agency (ACA), the city may enter in diverse drought states each of which entails several restrictions (leisure activities, irrigation, industrial uses, pressure reduction on the pipes, etc.).

The purpose of this water resources and drought model is to represent the water contributions that enter at the reservoirs at a monthly time scale depending on the precipitation fallen over the sub-basins of each dam.

Simulations of the volume contributions at each reservoir have been carried out applying an HBV model. The HBV is an integrated hydrological modelling system developed at the Swedish Meteorological Hydrological Institute. The model applies 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 and has been considered suitable to reproduce the reservoirs contributions over the Llobregat's and Ter's basins.

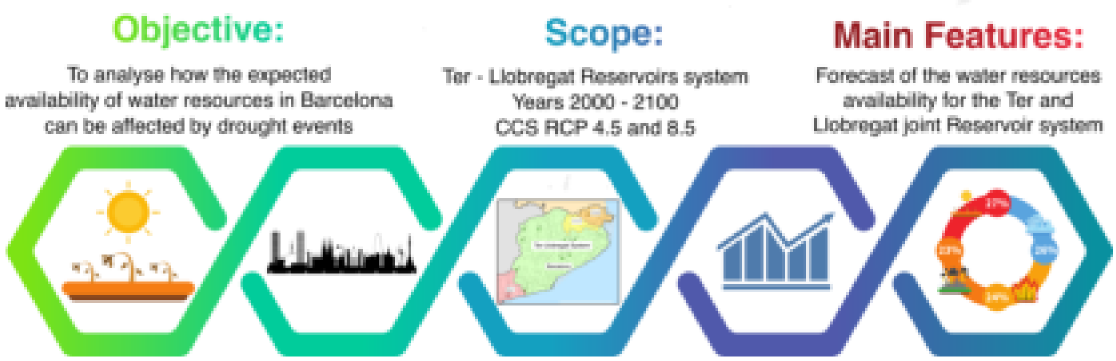


Figure 48: Summary of the drought model execution, key features, scope, and objectives.

As stated on Deliverable 2.3 (Russo, 2019),water availability will plausibly drop slovenly in this 21st century for the joint Reservoir system. Figure 48 presents a summary of the outcomes for the analysis of the joint system, analysing the impact of the Climate Change scenarios in the evolution of the water availability for the whole reservoir system. The intercorrelations among the nine executed models provided a trend line of the foreseen behaviour of the water volume in the reservoir system.

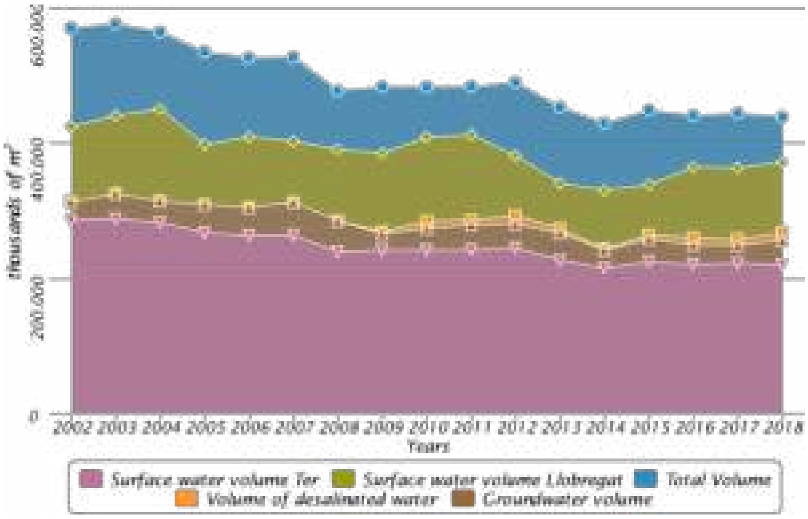


Figure 49: Evolution of water resources by type during the last two decades. Modified from (Agència Catalana de l'Aigua, 2017).

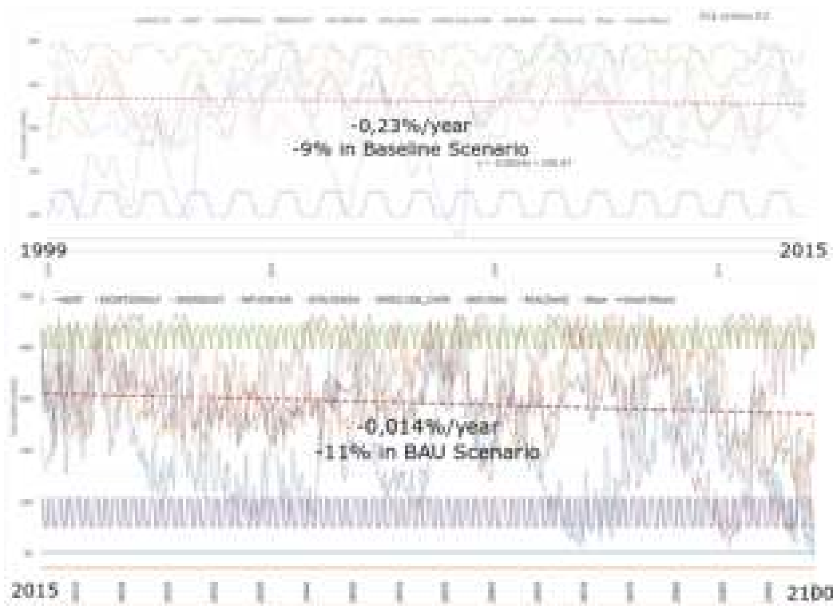


Figure 50: Results summary figure showing Range and average water volume results for Baseline (up) and BAU (down) scenarios.

By 2019–2100, the models average forecast an 11% water availability shrinkage with a remarkably high consensus among analysed models. Such changes in sustainable water availability would have city-scale consequences for social-economic conditions as well as for ecosystems.

2.8.2 Adaptation strategies, measures and design criteria

Alternative water resources must be considered during the following years since reservoir water reserves are at least enough to contribute to Barcelona water supply and to keep the reservoirs system balanced at the same time.

It is possible to affirm that thanks to the implementation of the Barcelona-Llobregat Desalination Plant in 2009, the adaptation measures from the stakeholders (such as "Drought Plan") and the incessant problems of water supply the city face, Barcelona put itself in a stronger position to better face eventual future drought problems. However, well-advised management of water resource is highly recommended, being primary to prevent reductions in the water supply.

Some practical solutions have been already defined into this Drought Plan developed by the Water Catalan Agency (ACA). They are related to an increase in alternative water sources and a decrease in drinking water consumption. As can be seen from the table (below), ACA defined warning thresholds as a function of water levels into reservoirs.

Table 23: Warning thresholds as a function of water levels into reservoirs considered by ACA.

Status	Threshold – Water levels into Reservoirs
Normality	Until 75% of water stocks
Pre-Alert	Less than 60%
Alert	Between 30-40%
Exceptionality	Around 20%
Emergency	Less than 20%

Depending on these thresholds, different solutions are taken into consideration, such as the planning and implementation of water reclamation and reuse, desalination as a technical option to increase the drinking water availability, to increase groundwater extraction, to decrease consumes (stronger for agriculture, water supply and recreative uses).

Other alternative solutions can be carried out to prevent water scarcity in the future, most of them are related to a water consumption reduction and a water supply network improvement. Some of the most useful adaptation measures that can be proposed are enlisted in Table 24.

Table 24: Proposed adaptation measures in long term period, with related stakeholders.

ID	Adaptation Measure	Details	Drought-related Stakeholder
1	Optimize desalinization plant production	To reduce desalinization cost through Improvements to forward osmosis, optimization of chemical dosing, implementing advances in pump design, increasing waste energy recovery from reverse osmosis	Desalinisation system administrator - ATL - Ens d'Abastament Ter Llobregat
2	Promote the use of grey water in new housing developments	Promote the use of grey water in new housing developments and renovations or for industrial purposes, and study its inclusion in future versions of the municipal urban environment by law	Government, private sector

ID	Adaptation Measure	Details	Drought-related Stakeholder
		To establish economic incentives to modern Water and Wastewater Reuse Solutions	
3	Continue reducing leakage in water distribution networks	Perform monitoring, preventive and corrective actions to avoid leakage problems in water distribution networks through pressure management, improving hydraulic models of the water supply network, with a complete pipe inventory and calibrating leakage coefficient, using fixed pressure reducing valves to improve pressure variation events	Aigües de Barcelona, Agència Catalana de l'Aigua, ATL
4	Study the feasibility of producing regenerated water at the Besòs WWTP to feed the Besòs aquifer, to maintain the river's ecological flows and feed the purification plant	Study the feasibility of producing regenerated water at the Besòs WWTP to feed the Besòs aquifer, to maintain the river's ecological flows and feed the purification plant	Aigües de Barcelona, Agència Catalana de l'Aigua, ATL
5	Exploit the Besòs aquifer resource as potable water and build a purification plant	Exploit the Besòs aquifer resources as potable water, for a new drinking water treatment plant	Government, private sector
6	Use regenerated water from the Llobregat River for the industrial uses of the Zona Franca Consortium and for recharging the aquifer	Utilise regenerated water from the River Llobregat for the industrial uses of the Zona Franca Consortium and for recharging the aquifer, and increase the water flow on the river	Government, private sector
7	Promote rainwater collection and its reuse in buildings	Promote rainwater collection and its reuse in buildings To establish economic incentives to implant modern SUDS and rainwater collection infrastructure in residential and business sectors	River Basin Authority, government, private sector
8	Inter-basins connections	Inter-basin connection to offer redundancies for water supply	River Basin Authority, government, agricultural sector
9	Increase the water cost for specific uses	Increase the water cost (to reduce water consumption) through different actions: tax for water overconsumption in industry processes, incentives to modern irrigation systems development or to a change in agricultural production (promoting more sustainable farming)	Government, industrial and household sector

However, these solutions have significant technical, legal, and political hurdles. They provide substantial collective benefits to the public and biodiversity, suggesting that such solutions may be appropriate for implementation via multi-stakeholder collaboration. These alternatives involve a water resource optimal allocation by the manager at all administrative levels.

To establish economic incentives to implement modern plumbing supplies for minimal water consumption in the residential sector requires additional costs. This could create a gap between potential households adopting this technology, and how many users would omit these improvements. To identify and model a variety of demographic and household characteristics, social network influence, and external factors such as water price and rebate policy to see their effect on residential water conservation technology adoption, are basic steps to implement this adaptation measure. Table 25 defines the costs of the adaptation measures required to face the estimated water shortage for the city of Barcelona at present as reported by various sources.

Table 25: Adaptation measures to handle Drought, average costs per m^3 of water.

ID	Adaptation measure	Maximum potential (Hm^3/year)	Maximum potential (m^3/s)	Average unit cost (euros/m^3)
1	Optimize desalinization plant production	60.00	1.90	0.58
2	Promote the use of grey water in new housing developments	6.60	0.21	2.05
3	Continue reducing leakage in water distribution networks	18.11	0.57	0.78
4	Study the feasibility of producing regenerated water at the Besòs WWTP to feed the Besòs aquifer, to maintain the river's ecological flows and feed the purification plant	63.80	2.02	0.50
5	Exploit the Besòs aquifer resource as potable water and build a purification plant	6.06	0.19	0.46
6	Utilise regenerated water from the River Llobregat for the industrial uses of the Zona Franca Consortium and for recharging the aquifer	3.90	0.12	0.55
7	Promote rainwater collection and its reuse in buildings	6.36	0.20	2.05
8	Inter-basins connections	189.96	6.02	0.56
9	Increase the water cost for specific uses	3.48	0.11	0.02

Sources: Water Change, 2011; (Luque Montilla, 2010) ;(Barcelona Regional, 2018); Catalunya and Ambient, 2012, UK National Audit Office, 2000.

2.8.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

The implementation of the proposed adaptation measures cannot be directly integrated into the statistical model used to describe the hydrological behaviour of water resources in the city.

The HBV hydrological model handled and analysed raw historical precipitation data from the perspective of the climate projection models discussed earlier in this document. The nature of the input and output dataset used in the model does not allow characterising the impact of the adaptation measures on the identified risk, as the measures do not change the natural rainfall regime, so they do not influence any possible change in the model's parameters for subsequent adjustment of the execution of these measures. The proposed approach is to observe the impact of adaptation measures to obtain a reduction of hazard and risk, bearing in mind that all the proposed adaptation measures tend to increase the availability of the water resource, it is possible to verify its influence according to implementation scenarios according to its water potential.

Considering the projected lack of water resources for the BAU scenario - 10,88 hm^3/year - determined in Deliverable 3.4 (Evans, 2019), the maximum potential use of adaptation measures will be adopted to create possible mitigation alternatives to alleviate the projected deficit of water resources, in terms of volume of water. The analysis of derived costs for the implementation of the different adaptation scenarios is deeply discussed in Deliverable D3.6.

2.9 Llobregat river and Sant Joan Despí treatment Plant: Turbidity model

The Sant Joan Despí DWTP supplies nearly 50% of the drinking water to the city of Barcelona, producing nearly 300,000 m^3 of drinkable water from the Llobregat River. This potabilization process is interrupted by high turbidity events in the Llobregat River since the coagulation and flocculation stages within the treatment handle turbidity limits, over which the plant cannot operate.

The maximum admissible turbidity values for the water at the Llobregat River is 500 FNU (Formazin Nephelometric Units) under normal conditions and 1000 FNU in drought seasons, to comply with the drinking water treatment process execution. When a high turbidity episode occurs, the raw water intake of the water treatment plant must be closed during the time that turbidity limits in the river are beyond the threshold.

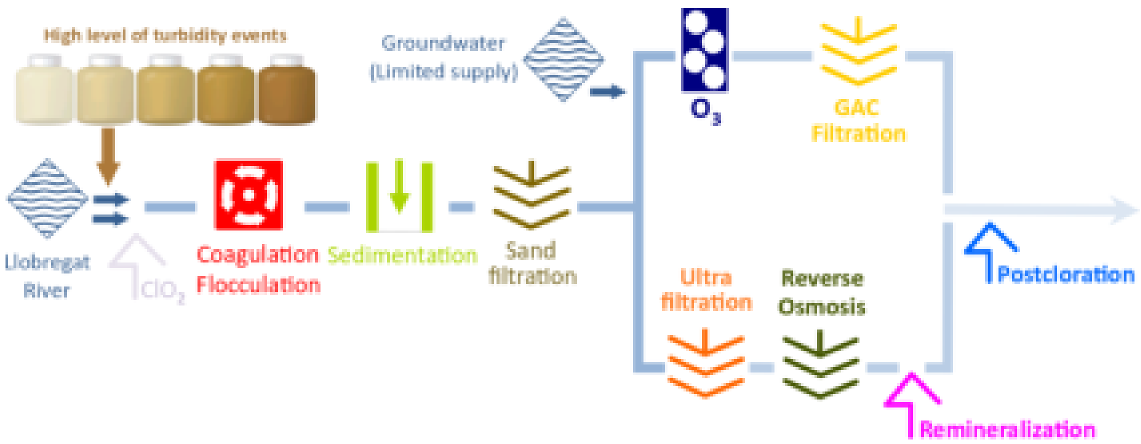


Figure 51: Operation scheme of the Sant Joan Despí DWTP. Modified from (Saucedo and Bosch, 2018).

One of the most important parameters that define the existence of these high turbidity events are the episodes of precipitation, for which a statistical model was developed that correlates the high turbidity phenomena, therefore the DWTP operation closes, with precipitation events in the Llobregat River basin, as indicated in Deliverable 2.2 (Russo, 2018a).

Figure 52. Summary of the turbidity model execution, key features, scope, and objectives.

2.9.1 Summary of specific climate hazards and risk for the water supply on Barcelona city

As reported in Deliverable 2.3 (Russo, 2019), by confronting the two trends projected under the Baseline and BAU scenarios it was assessed that there are no significant differences in the evolution of the DWTP closure events due to high turbidity phenomenon.

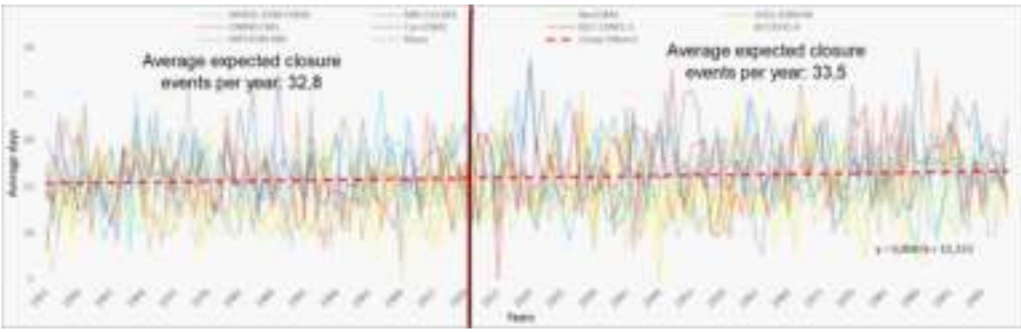


Figure 53: Average days in a year with turbidity events exceeding 500 FNU for baseline scenario (left) and according to Climate Change models for BAU scenario (right). The red-dashed line provides the general trend line

The technical, economic, and social impacts were outlined in Deliverable 3.4 (Evans, 2019). Despite the potential lack of drinking water supply due to operational disruptions of the DWTP by high turbidity events, the possible impacts are greatly mitigated because of the technical alternatives already generated to solve the existing problem in the sort of redundant water sources. The average duration of 5 hours per plant closure event has been determined due to high turbidity, and throughout this time it is necessary to adopt alternative sources, as it is not economically viable to build storage systems for a volume of water that can supply the city of Barcelona.

2.9.2 Adaptation strategies, measures and design criteria

Analysis of the turbidity variations shift brings about more information about source quality, the efficiency of treatment of the raw water and understanding of processes within the chain of the drinking water production. Based on the analysis performed by this study, more effective application of the regulations for better basin management including soil-water conservation in watershed is necessary. Furthermore, Sant Joan Despí DWTP needs to prepare and ensure the adequate operation of water treatment with high raw water turbidity (e.g. >500 FNU), a coagulation pre-treatment process might improve the capabilities of the DWTP handling the high turbidity events.

Other climate change adaptation strategies such as off-line storage, operational changes in distribution systems, or the use of supplemental water sources including reclaimed or recycled water should be taken into consideration to increase drinking water availability in failure events. The installation of a selective withdrawal facility into a reservoir can be performed considering the timing of extreme events (i.e. the imminence of a flash flooding event) to mitigate the impact of high turbidity on the water supply and downstream ecosystem. Coping with the worst event expected to occur in the future would require additional countermeasures such as bypassing high-turbidity water.

It was observed that the main cause of deterioration in water quality was due to the lack of proper sanitation, unprotected river sites, high anthropogenic activities, and direct discharge of industrial effluent, besides the heavy rainfall events. Most of these situations can be alleviated. The forecast of a raw water intake closure event is technically challenging. In recent years, researchers have investigated a variety of approaches including new sensors, decision algorithms to distinguish and characterize turbidity sources, the use of the smart technology within the European project "SmartWater4Europe", among others, which are able to measure the variation of the Turbidity in upstream points as the current one in this study.

Adaptation measures non-related to the optimisation of DWTP operations facing high turbidity levels are positively linked to increasing the availability of water resources in the city of Barcelona, so the same measures to deal with drought events are applied in this case, as these measures aim for the same objective, to ensure the population's access to water. Proposed adaptation measures to face disruption events on DWTP in long term period, with related stakeholders are shown in Table 24.

Analyzing the scale of the proposed adaptation measures, it is not possible to implement such measures to cope with high turbidity events on the scale or in the way they would be performed to cope with drought, since high turbidity events on average do not exceed 23 hours in duration, and a drought period can last for months. Table 25 defines the costs of the adaptation measures required to face the estimated water shortage for the city of Barcelona at present as reported by various sources.

2.9.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

The impacts of the implementation of adaptation measures on extreme turbidity events cannot be modelled using the current rainfall model, as the measures do not modify the expected precipitation trends.

The use of alternative sources that fill the void of water demand generated by these events of high turbidity in the surface source has higher associated costs than those of the traditional source of water. The water utility company may require significant capital investments such as additional treatment unit processes, source water storage, distributed network modifications, or paradigm shifting (direct/indirect reuse) to avoid future recurrence of the service disruptions.

High turbidity events in the Llobregat River hold a great interrelation with rainfall extreme cases, which has helped to characterize and represent the projected behaviour, at least, of the expected number of days with disruption of the DWTP services.

Comparable to the state discussed for drought phenomena, none of the proposed adaptation measures can be introduced to the hydrological model in order to obtain a separate output, because such model analyse rainfall patterns, and, the proposed adaptation measures do not change the projected rainfall regimes, but are conceived to face the lack of drinking water in the time frame that the high turbidity affects the operation of the DWTP.

The implementation of the adaptation measures will reduce the risk originated by the DWTP closing events due to high turbidity levels in the water source, providing the enough drinking water flow to satisfy the demand during the service disruption time. The analysis of derived costs for the implementation of the different adaptation scenarios is deeply discussed in D3.6.

2.10 Conclusions about adaptation strategies implementation for Barcelona Research Site

Within RESCCUE project and according to Barcelona Climate Plan, the following 4 adaptation strategies have been defined and analysed with the aim to face with flood and drought problems potentially exacerbated by climate changes are:

- Flood impacts reduction in a context of climate change
- Environmental improvement of receiving water bodies
- Guarantee security service supply
- Ensure the drinking water availability through alternative water resources

All these strategies have been fully analysed in the context of WP2, WP3 and WP5. Some of them (mainly related to flooding and CSOs problems) aim to reduce impacts acting on the hazard reduction, while other ones (mainly related to water resource guarantee) aim to minimize the vulnerability of the system promoting resilient measures. Hazard reduction for the first two strategies has been assessed using sectorial and integrated models described in the previous deliverables of WP2 defining, for each of them, two different adaptation scenarios according to the progressive implementation of selected adaptation measures. For these two strategies, the assessment of the hazard reduction due to the implementation of a set of measures has been described in the previous sections. Particularly the two strategies and adaptation scenarios that have been simulated can be summarized as follows:

- For both strategies, flood impacts reduction and environmental improvement of receiving water bodies, Sustainable Urban Drainage Systems (SUDS) and structural measures have been defined and simulated in order to assess their effectiveness in terms of hazard reduction (risk reduction is assessed in WP3).
- For all the city sectors facing flooding (urban drainage, electrical system, waste system and traffic) and beach sector facing CSOs impacts, it has been demonstrated the significant effects of SUDS implementation in terms of hazard reduction, although they cannot eliminate flood hazard for medium return periods like 10 yeras. The complementary implementation of SUDS and structural measures is able to avoid flood hazard for low and medium return periods (up to 10 years) and accomplish with the current legislative framework for the case of CSOs limitation in bathing waters.
- The measures concerning the guarantee of water service supply and the ensuring of drinking water availability have been defined and discussed, but their efficacy will be assessed by impacts models in WP3.

3 Assessment of climate hazards reduction for Bristol Research Site

3.1 Summary of multi-hazards and multi-risk assessment for Baseline and BAU scenarios

With a population of approximately 449,300 Bristol is amongst the most densely populated regions in the UK. A rapid rate of growth is apparent in the central area which also comprises the main business hub and economic centre. The maritime climate influenced by the Atlantic Ocean and the European continental mainland make for variable weather conditions. The range of land topography contributes towards to the varying effects of weather systems felt throughout the city. Bouts of heavy or prolonged rainfall are climatic factors posing a significant citywide flood risk. This pluvial flood risk is heightened especially due to the heavily urbanized nature and predominant clay soil land coverage providing rapid run off and generally poor infiltration characteristics. Fluvial flood risk has been reduced in parts due to the implementation of large culverted interceptor tunnels diverting river flows however a risk associated with this source of flooding is still apparent in places. The tidal River Avon flows through the city in a westward direction and is influenced by the 14m tidal range of the Severn Estuary where it discharges. This causes a significant tidal flood risk to many riverside areas adjacent to the watercourse, the adjoining Floating Harbour and to the lower reaches of its tributaries. The risk of flooding is predicted to increase going into the future with the expected impacts of climate change and in Bristol the effects of heightened river flows, sea level rise and increased storminess will have severe consequences.

Several Risk Management Authorities operate within the region covering responsibilities for the various sources and aspects of flood risk. This includes Bristol City Council (BCC) for surface water, groundwater and highway flooding. The Environment Agency (EA) for Main River and coastal flooding. Wessex Water (WW) for sewer flooding and the Lower Severn Internal Drainage Board (LSIDB) for a low lying series of drainage ditches known as the Avonmouth rhine network in west Bristol. Fresh drinking water provision and flooding problems associated with this type of risk is managed by Bristol Water. Vulnerable services include a transport network comprising the highway network and railway infrastructure. Further detail and information behind the population, demographics, climate, morphology, geology, watercourses and their related hazards associated with the city of Bristol are contained within Deliverable 2.1 (Vela, 2017). Further information about those organizations managing the risks and details of key infrastructure providers and utility services providing critical functionality in the city are explained in further detail in the aforementioned deliverable.

Several sectorial models have been developed within the Bristol research site in order to assess the hazard risk. This includes two joint probability combined tidal and fluvial flood models utilising hydraulic and hydrological modelling to construct a 1D river network, represented using ISIS software and 2D ground surface in TuFLOW software. One such flood model covers the west of the city at Avonmouth inclusive of a series of drainage channels known as the Avonmouth rhine network and impacts from the Severn Estuary. Another covers the city centre central area considering the Floating Harbor, River Avon New Cut and surrounds. There is also a citywide Surface Water Management Plan (SWMP) flood model looking at pluvial flooding from a variety of different heavy rainfall events. The SWMP comprises an Infoworks ICM 1D sewer network model and a new 2D detailed ground surface model. The SWMP entailed providing an integrated analysis of flooding problems involving piped sewerage systems and open watercourses as well as overland flow. All of the aforementioned flood models have depth, velocity and hazard mapping for the current day and inclusive of climate change impacts in the future and are available in ArcGIS grids. Estimated flood levels for critical return periods and flood flow routes, natural flow paths and identification of blue corridors are readily available from this data source. Integrated flooding-electrical and flooding-traffic models also exist, developed in order to quantify the risk posed to these critical services during various types of flood events. Deliverable 2.2 (Russo, 2018a) provides greater explanation and detail around these sectorial models which is summarized in Table 26 below.

Table 26: Bristol sectorial models summary.

Model type	Model format	Hazard assessed
Urban drainage model	1D/2D Integrated Urban Drainage Model – 1D sewer network and 2D ground surface (Infoworks). Model completed using Microdrainage WinDes software, FloodFlow package	Multiple return periods and durations to reflect present day and future surface water pluvial flood risk caused by heavy rainfall events
Tidal and Fluvial Flooding models	1D/2D model of the tidal and fluvial systems in central Bristol and at Avonmouth, including assessment of joint probabilities. Hydrology calculations include an allowance for climate change. Model developed in ISIS (1D river network) and TuFLOW (2D ground surface) software	Combined fluvial tidal joint probability flood scenarios for a range of return periods now and in the future
Integrated flooding - traffic model	Open Source Micro-Simulation Traffic model loosely coupled with 1D/2D Flood Models	Pluvial and tidal flood events in the present day and future
Integrated flooding - electrical model		Pluvial and tidal flood events in the present day and future

The main results for the current and BAU scenarios helped identify high risk areas at localities throughout the city associated with different sources of flooding. Making for the development of emergency response plans dependent on prevailing weather conditions and for producing climate adaptation strategies. Areas identified as subjected to high surface water flood risk include Ashton, St George, Dundry and Southmead although the sporadic nature of this type of flooding is also shown in the modelling. Notable increases in such areas were demonstrated in the climate uplift modelling where it was observed that a current day 200 year pluvial flood extent is predicted to look comparable in its coverage to a 100 year pluvial flood extent in the 2110s epoch. The exceedance of tide flaps, that allow for piped river discharges to the tidal watercourse, has increased substantially in the future due to sea level rise putting a burden on such flow points and consequently causing backing up of the system and subsequent surcharging during high tides and heavy flows. This phenomenon it is also shown puts a tremendous strain on the Ashton Avenue Sewer Pumping Station that serves the low lying riverside area of Ashton. The river and tidal flood models concluded that the Avonmouth area is at more of an immediate threat to tidal inundation in the future climate epochs highlighting the need for flood defences protecting this area. The central area and in particular the areas at Spike Island, Hotwells and St Philips Marsh are particularly susceptible to tidal flooding whereas further upstream at Netham there is the switch to fluvial flooding predominance. All areas are exposed to significant risk in the future due to expanding flood extents, increased depths, velocities and resultantly flood hazards. Deliverables 2.3, (Russo, 2019) and (Russo, 2018b) elaborate on these results and findings in further detail.

3.2 Adaptation strategies and measures to cope with climate change for the city of Bristol

Climate adaptation strategies in place in Bristol and enacted by the local government authority are summarized in Table 27 below.

Table 27: Bristol City Council climate adaptation strategies.

Strategy Name	Background	Strategy Measures
Green and Black	Inclusiveness and environmental awareness are key concerns for Bristol now and in the future.	• Long term series of activities and relationships with Black and Minority Ethnic (BAME) communities • Developing young BAME ambassadors to raise environmental awareness in their communities and more broadly around the city.
Community-based adaptation	Communities that are self-organized in daily life are inherently better prepared to respond to, and recover from, unexpected events in their neighbourhoods.	• A multilevel, cross-sectoral approach involving a range of different stakeholders – including the residents themselves - is necessary to develop adaptive capacity and build long term resilience. • Following the Community Based Approach (CBA) to develop a more integrated and inclusive way to working with communities and empower them with the knowledge, confidence and resources to take action when affected by local shocks.
Legible City	A 20 year old project based on the unique concept to improve people's understanding and experience of the city through the use of identity, information and transportation projects.	• Develop innovative city mapping and information resources to support change to more sustainable forms of transport and encourage active travel choices • Deliver a suite of digital, printed and street-based information products to encourage residents and visitors to explore the city on foot, bike and using the public transport system • Enhanced pedestrian wayfinding system across the city and develop new user-friendly information for the cycle network, the MetroBus project and the wider public transport system • Improving communication of sustainable and active travel options to increase citizen take up and help improve wellbeing and reduce congestion.

Bristol Transport Plan	20 year plan to shift usage to sustainable transport in Bristol. Lowering car journeys and increasing active travel to protect the environment, improve air quality, health and reduce carbon emissions and congestion.	• Deliver new transport infrastructure to reduce congestion, carbon emissions and ensure infrastructure is resilient to climate change • Work with Massachusetts Institute of Technology Smart to quantify the impact of different transport options • Use 50 year scenarios to support strategy development, and ensure other transport strategy projects are integrated with this longer-term view
Clean air city	Actively engage European citizens in measuring their personal impact on air quality and CO_2 emissions in their cities.	• Use innovative tools like specially made apps and games for smart phones to generate citizen-led policies to improve air-related health in our cities • Thousands of people across Europe will be invited to share their views on how to reduce air pollution and improve related public health in six pilot cities. Residents will use a game on their smartphones, tablets and laptops to suggest how their home cities should develop in the future. The result will be directly translated in improved city policies • In Bristol the focus will be on raising awareness about poor air quality and work with citizens to identify simple actions that can improve air quality in their local streets
Climate change adaptation plan	A plan will be developed to future-proof the city by identifying the major climate hazards and their potential impact	• A framework for adaptation, and identification of strategies to build climate resilience • Consideration of the issues will be required at a city scale with actions targeted at a local scale with their benefits well communicated
Establishing a resilient city financing structure	Establish a Resilient city financing structure by aggregating a suite of small and large scale place-based projects focusing on improving local resilience	• Blend public and private money and take a long term view (at least 25 years) to achieve a social as well as a financial return on investment on flood defences, green infrastructures, community facilities and new housing • Provide key infrastructure assets and jobs in order to facilitate this

Manage our future flood risk	Rising sea levels will accelerate due to the impact of climate change, causing the likelihood of tidal flooding in central Bristol	• Recommend an adaptive program to identify when flood risk management interventions are needed and examine how they will be funded to ensure continued and sustainable growth in the city's economic hub
Wild rainwater streets	Greening local neighbourhoods helps to make our city more liveable, whilst also improving local biodiversity, enhancing sustainable drainage, and reducing the urban heat island effect and improve the city's resilience to climate change.	• Build on existing initiatives, including Avon Wildlife's Trust's My Wild Street, Wessex Water's Rainwater City, and Embleton Road SuDs, to develop an approach that communities across the city can engage in.
Protecting and valuing green space	Develop a high level assessment of the financial value of green spaces across the city to assist with future investment decisions	• Valuation analysis of the natural capital in Bristol's parks will be conducted, which includes certified values of each ecosystem service. • Provide an evidence base to support increased uptake and delivery of green infrastructure projects, both improvements to existing green space and delivery of new projects
Natural Capital Trust (NCT)	An innovative mechanism to deliver enhancement in the quality of the natural environment across the West of England region	• Provide support to the wider NCT project • Identify and implement funding from developers, and from potential beneficiaries of Payments for Ecosystem Services schemes, to support a range of projects which ensure provision of services by ecosystems, enhancing (amongst other things) resilience to the effects of climate change and of the region's infrastructure
Urban Integrated Diagnostics	Research and innovation initiatives that help to improve the city's health, well-	• Bring citizens together with researchers, local authorities and partners from business and the voluntary and community sector aimed at investigating the very real challenges facing the city across four areas: mobility and accessibility, health

	being and prosperity as they face up to challenges of modern urban living	and happiness, equality and inclusion, and tackling dependency on fossil fuels • Learn from other pilot cities of York, Leeds, Newcastle & Gateshead, and Birmingham • Learn and adapt, improving our knowledge, helping to tackle stresses such as inequality and transport congestion
Resilience Impact Assessment	Major initiatives and investments in BCC are subject to an Environmental Impact Assessment (EIA)	• Provide an integrated and systemic view of risks and impacts associated with city interventions • Consider how resilience is embedded into design and implementation of city and regional projects • A group of officers will be convened in the BCC to develop proposals for integrating resilience thinking into internal assessment processes
Resilience and West of England (WoE) devolution deal	Devolution from central government of funding and powers to the WoE region, including decisions regarding transport, investment, funding, skills training, business support, housing and strategic planning.	• Workshop held to explore how devolution of funding and powers could improve city resilience through integration into the new governance structures • Embed resilience into those areas of devolved powers of skills, infrastructure, and strategic planning
British Standard on city resilience	Development of a good practice guidance standard in relation to city resilience	• Bristol, amongst other 100RC cities, will host a workshop to inform the development of the standard, peer reviewing the intended approach • The standard will act as guidance for the city leaders and as a management framework for executives with responsibility for different resilience themes within cities.
Climate Strategy and Energy Framework	BCC has created the 'Framework for Climate and Energy Security' as part of being European Green Capital in 2015	• Low carbon plan to reach the target for Bristol to be Carbon Neutral by 2050 • Plan to be reviewed and refreshed every three years to provide a continuous process of improvement • Provide continuity of energy supply

Adaptation & resilience framework for the Bristol Avon catchment	Multi-agency collaborative initiative to identify opportunities and risks for organisations by climate change disruption and economic austerity	• Greater integration of actions across sectors and political boundaries working at a catchment scale • Engaging with other key strategic planning organizations and infrastructure providers to understand the interdependent risks and opportunities and deliver cross-sectoral adaptation actions in spatial planning at a catchment scale • Deliver multi-beneficial outcomes from collaborative investments from regional natural capital distributed to multiple locations • Ensure strong regional economy and enduring infrastructure supported by sustainable agriculture and resilient natural capital • Plan an integrated way for the long-term resilience of the WoE region's natural resources
Clean Air for Bristol	Initiative to address the city's failings in meeting the legal requirements for air pollution rates	• Monitoring to retrieve pollutant data, such as for oxides of Nitrogen and particulate matter • Declare Air Quality Management Area within worst affected areas and suggest actions to combat this • Develop Clean Air Zones and charge the worst polluting vehicles and improve air quality • Improve walking, cycling and bus usage • Work with bus operators to clean up the bus fleet • Ensure BCC fleet of vehicles is clean, by using electric pool cars, some electric vans, some other ultra-low emission vehicles (ULEVs) and providing training for drivers • Work with providers to increase the number of EV charge points and implement the Metrobus rapid transit service • Plant 50,000 trees • The MetroWest project will improve existing rail provision across the sub-region, including the opening of new stations and increased frequency on local lines. • Large-scale investment in walking and cycling through the Cycle Ambition Fund which is creating new routes and improving existing infrastructure. • MetroBus, a rapid public transport system that will provide an express service to key destinations in the

		area using a combination of segregated busways and lanes, will use low emission vehicles. • Ensuring the council fleet vehicles are modernised to reduce pollution by replacing out of date diesel vehicles. This being supported by a £7 million project to provide over 200 more public and business charging points across the city region. It will also enable people to buy new electric cars with confidence that they can charge them. • Increasing the proportion of electric pool cars available for council employees to use on city trips. • Changes to Taxi Licencing Policy to improve taxi fleet emissions • The whole of Bristol is a smoke control area (SCA) which aims to ensure emissions from solid fuel are controlled to some extent

Apart from the strategies listed above, in the framework of RESCCUE project five new strategies have been defined. If it is a measure of the list please specify:

1. Learn from real life flooding by recording and investigating events
2. Create and maintain a flood risk asset register to identify key flood risk assets and who is responsible for their maintenance
3. Identify high risk areas by conducting studies involving flood modelling analysis
4. Develop community flood plans
5. Build riverside flood defense walls

A number of Adaptation Strategies are now being investigated and modelled to reduce the level of impacts within the city. Those with the necessity for further investigation and analysis linked to the sectorial flood modelling include number three and five from the above list:

- Identify high risk areas by conducting studies involving flood modelling analysis
- Build riverside flood defense walls

On reflection and interpretation of the flood impact analysis the above adaptation strategies have been produced and modelled to quantify the benefits derived from their implementation. A further breakdown of specific measures compiled to fulfil the strategies has been scoped out. In reference to the Ashton area this includes increased sewer pumping capacity at Ashton Avenue Sewer Pumping Station, making structural improvements to critical flood risk assets, channel modifications on the Colliter's Brook watercourse or making wider catchment runoff reductions within the contributing area of the Ashton catchment. In respect of the St Philips Marsh area the constructing of flood defense walls along the River Avon to address low spots is aimed to eradicate tidal ingress at these points and the adjoining Bristol central area thus nullifying the high tide impacts and providing its associated flood damage limitations.

3.3 Urban Drainage Sector

3.3.1 Introduction and summary of climate hazards for the urban drainage sector

Section 4 of Deliverable 2.2 (Russo, 2018b) provides a full description of the drainage systems serving Bristol and the modelling work undertaken to understand their performance and flooding risk.

Like most long-established cities, the city of Bristol is served by numerous drainage systems:

- Natural rivers
- Smaller (natural) watercourses
- Man-made ditches and culverted watercourses
- Surface water sewers
- Foul sewers
- Combined sewers

All of the foul and combined sewerage network serving Greater Bristol (including areas outside of the city) 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 a population of 44,000.

The great majority of Bristol is served by a combined (foul and rainwater) system, however the more recent developments (post-1970) are 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.

There is considerable interaction between the various urban drainage systems and this is reflected by using an integrated modelling approach for the city-wide Bristol catchment and, in more specific detail within the Ashton Vale study sub-catchment. Key interactions between systems include:

- Tidal / river level constraints on surface water and CSO outfalls ("tidelocking")
- Overflow from watercourses & surface water culverts to the combined sewer system
- Discharges from CSOs to surface water systems and watercourses
- Inflow from natural watercourses to man-made drainage ditches, surface water sewers and culverts
- Flooding out of watercourse channels to urban surfaces
- Flooding out of (combined and surface water) sewers to urban surfaces

While the verified 1D sewerage model was applied city-wide, the 2D modelling of flows across the urban surfaces was done within seven discrete hydrological catchments, including the Ashton Vale study area.

Within the Ashton Vale study area, the flooding risks can be broken down into 4 main categories. In descending order of perceived risk severity these are:

- Flooding from the Colliters Brook watercourse (bank overtopping at low points)
- Flooding from the combined sewer system
- Flooding from the surface water systems

- Surface ponding (flow being unable to drain away adequately due to inadequate provision or location of gully inlets (and blocked gully inlets)

The first three causes are also influenced by the level in the River Avon, which is dependent on tidal state and flood flows. Each of the above risks will be examined in turn, following a brief overview of the influence of the tidal River Avon.

Overview of Tidal and River Influence

Critical parts of the Ashton Vale area are at a lower elevation than the river banks. The banks were artificially raised in the early 19th Century when the New Cut river channel was dug and are now at an elevation of between 8.5m and 14.0m AOD. By contrast, the lowest ground elevation is 6.3 - 6.8m AOD (public open space / parkland), with roads and properties at 6.8 -7.5m AOD or higher. Under Highest Astronomical Tide (HAT) conditions, the river level can be as high as 8.2m AOD (and potentially as high as 8.4m AOD if storm surge and flood flow conditions also coincide with HAT).

The Colliters Brook and surface water sewers outfall to the River Avon by gravity outfalls, protected by tide flaps (non-return valves). When high tide level exceeds the outfall level, flows back up within the the Colliters Brook (which is in culvert for the 543m upstream of the outfall). Similarly, flows back up within the surface water systems discharging to the River Avon or to the Colliters Brook.

The foul/ combined sewer system has a major sewage pumping station (SPS) at Ashton Avenue which takes flow (from a population 136,000) in the southern and central parts of Bristol (this is more fully described in Section 3.2.3 of Deliverable 3.4 (Evans, 2019)). During storms when flows exceed the pass-forward flow capacity of the SPS, the excess is pumped up to a high-level fine (6mm) screening chamber from where screened flow gravitates to the river. If the stormflow is so high that it exceeds the total pumping capacity at the SPS (about 9.6 m^3/s) then the excess is diverted to an unscreened gravity overflow, fitted with tide flaps. This gravity overflow can only discharge when the flow level in the surcharged trunk sewer is higher than the river level. In extreme conditions (when all pumping capacity is beaten and high tide conditions prevail), flow level in the sewer can back up to ground surface level. Flooding of low-lying areas from the combined system can thus occur if the storm is of sufficient intensity and duration and is coincident with very high tide conditions.

The Ashton Avenue SPS was originally designed to accept stream flow from the Colliters Brook under tide-locking conditions (extreme high tides) via an overflow structure on the main surface water system and syphons on the Colliters Brook culvert which allowed excess watercourse flows into the combined system – and thus be pumped against high tide when necessary. The syphons are currently blocked off but the overflow structure is still in use to provide a degree of flood protection to the surface water system - however when this operates it increases the risk of combined sewer flooding in severe storms exceeding the pumping capacity at Ashton Avenue SPS (pumping capacity is exceeded by a storm of roughly 1 in 5 year or greater under current rainfall conditions, with significant flooding occurring roughly once in 30 years, and predicted to be more than 1:10 years by end-of-century). It also increases the frequency of combined sewer overflow to the river as it adds "clean" stream water into the wastewater system, which then also needs to be pumped and screened or treated. Combined sewer overflow typically occurs 30-35 times per annum from the SPS, based on recent telemetry data, equating to an average annual discharge volume of about 720,000 m^3/ annum. This is predicted to rise to about 50-55 times per annum by end of century under the BAU scenario, with a corresponding increase in discharge volume of 73% (1,246,000 m^3/annum). In order to predict and assess the likely impacts of climate change including sea level rise, increased storm intensity, frequency and heightened river flows the National Planning Policy Framework (NPPF) and UK Climate Projections 2009 derived uplifts were applied. The estimated change in future climate parameters was informed by the Met Office and UK guidance and sensitivity checked by the Madrid-based Climate Research Foundation (FIC) (see D1.3 for reference).

Flooding from the Colliters Brook

The Colliters Brook runs in open channel to a point roughly 1025m upstream of its outfall to the River Avon. It then goes into a culvert of varying dimensions for approximately 200 m under the railway line, a trading estate and the Winterstoke Road roundabout, emerging alongside the Ashton Gate football stadium, where it flows in open channel for approximately 275 m. It is this section which presents a flooding risk due to overtopping on the East bank. The Brook then goes back into culvert (circular, 1380 & 1800 mm diam) for 543 m to the River Avon outfall (see Figure 54 to Figure 61)

Under free outfall conditions, the final section of culvert has a pipe-full capacity of 5.0- 5.5 m^3/s (partly dependent on levels of siltation). The upstream section of culvert, under the Winterstoke Road roundabout, has a pipe-full capacity of approximately 1.5-1.6 m^3/s but it can convey over 2.3 m^3/s when surcharged. A large surface water sewer (950 mm diam, pipe-full capacity 1.05 m^3/s) also joins the Colliters Brook under the Winterstoke roundabout.

The first Colliters Brook culvert section and the open channel section do not have a steady downward gradient and about 270m are flat or backfall, as shown in the long section in Figure 62. Maximum conveyance of the open channel section at the onset of flooding is approximately 1.8 m^3/s, assuming a free outfall. Under high tide conditions (exceeding 6.5m AOD for more than 25 minutes) the culvert section and upstream channel would fill and flooding could occur under more moderate flows, possibly as low as 1.0m^3/s

Under free outfall conditions, modelling indicates that flooding from the Colliters Brook watercourse channel can occur for storms of 1 in 10 year return period under present day rainfall conditions, increasing to between 1 in 2 and 1 in 5 year return period under predicted end-of century rainfall conditions. However, if a storm rainfall peak were to coincide with high tide conditions (equating to Mean High Water Spring tide level, approx. 7.08mAOD), then flooding would occur for a 1 in 2 year storm (present-day rainfall) or a 1 in 1 year storm under predicted end-of-century rainfall

The impact of sea-level rise further increases the risk of flooding because the duration for which the critical tide level of 6.5mAOD is exceeded is predicted to rise from about 2.7% of the time (as at present) to about 7% of the time in a typical year, thus the probability of a stream flow exceeding 1.0m^3/s coincident with prolonged high tide means that the actual (combined probability) flooding frequency from Colliters Brook is about 1 in 5 year and could be as high as 1 in 1 year by century end unless mitigated.

Further work needs to be done to comprehensively model the combined probability risk of storm and tide using a long time series of observed or stochastic rainfall and tide data. This could be done as the next stage of scheme development ahead of any design work but is beyond the scope and timescale of the current strategic assessment.

Note: Responsibility for the management and maintenance of the Colliters Brook lies with the Environment Agency (EA) as it is classed as "main river" (this applies to the culverted sections as well as open channel). The EA are therefore responsible for flood prevention and improvement measures on the Colliters Brook and all other main rivers. The EA are now considering production of a comprehensive and detailed model of the watercourse systems in the Ashton Vale / Long Ashton area and this will be a valuable tool for design of future mitigation measures.

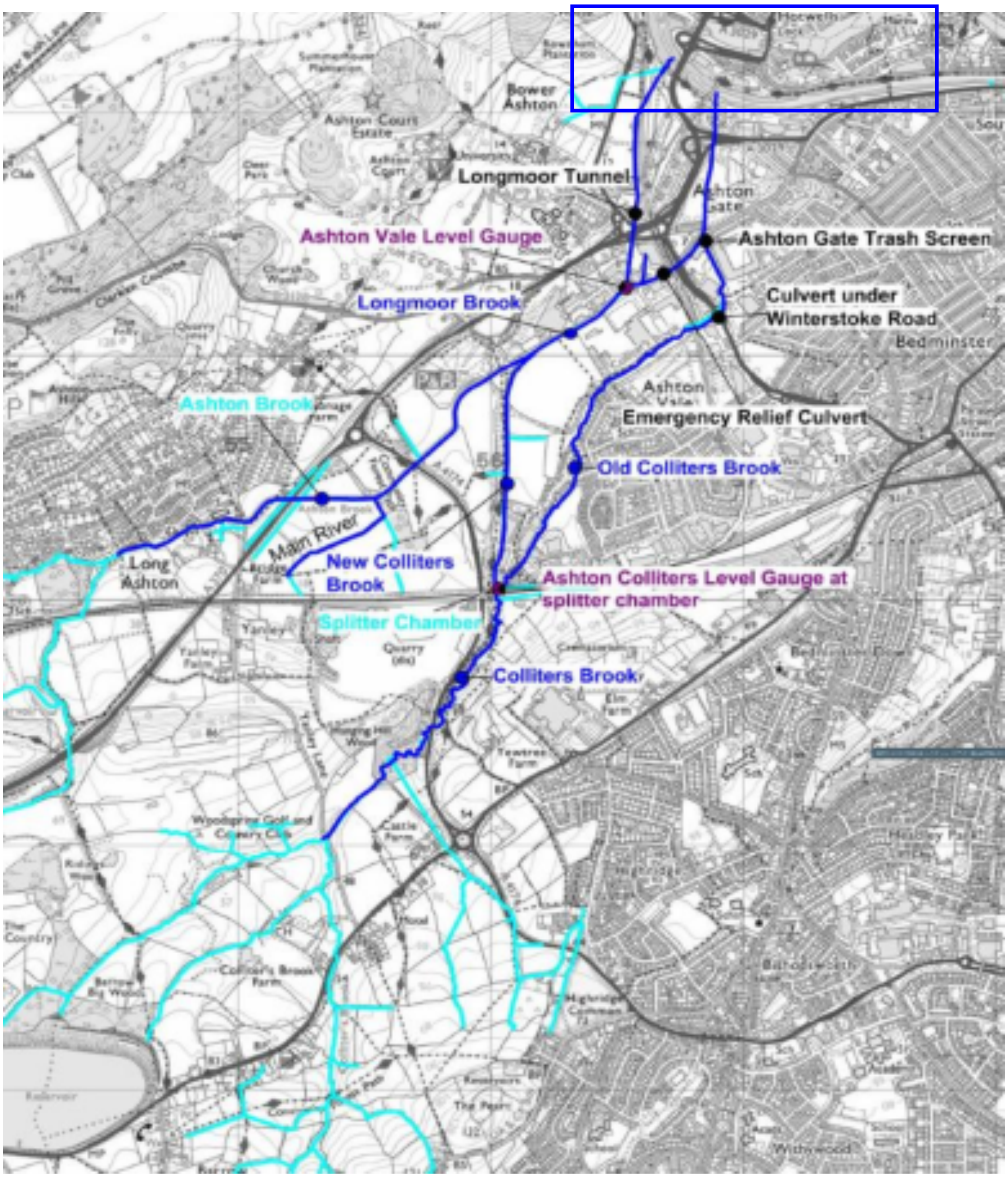


Figure 54: Overview of the Colliters Brook catchment and other watercourses in South West Bristol Ordinary watercourses shown in light blue, main rivers are shown in dark blue.

Figure 55: Aerial perspective of the Colliters Brook alongside Ashton Gate stadium.

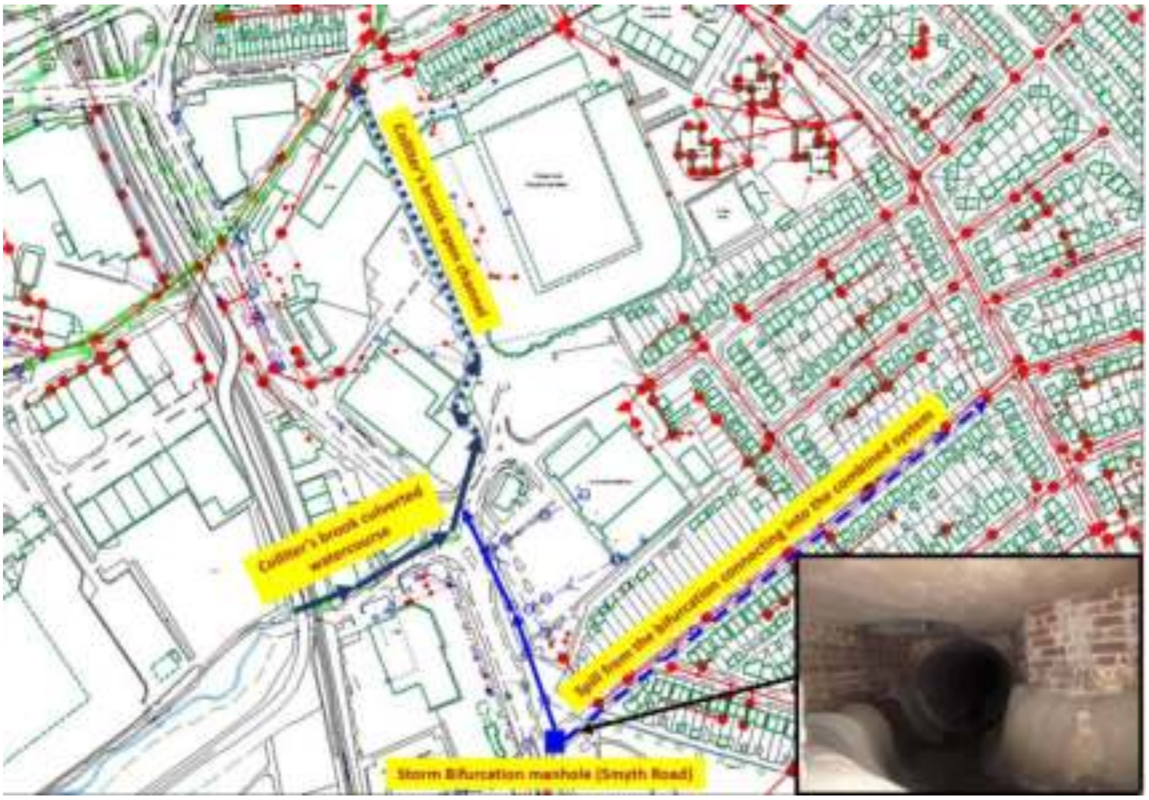


Figure 56: Colliters Brook culvert and open channel sections, showing overflow diversion structure from surface water to combined sewer system.

Figure 57: Open channel section of Colliters Brook prone to flooding (indicating survey cross-sections).

Figure 58: Colliters Brook culvert (1050mm dia.) and the overflow from watercourse to the combined sewerage system at Winterstoke Road/ Smythe Road.

Figure 59: Colliters Brook emerging from culvert to open channel section alongside Ashton Gate stadium.

Figure 60: Colliters Brook alongside Ashton Gate, showing partial flood walls (left) and Inlet to final culvert (right).

Figure 61: Outfall to the tidal Avon river.

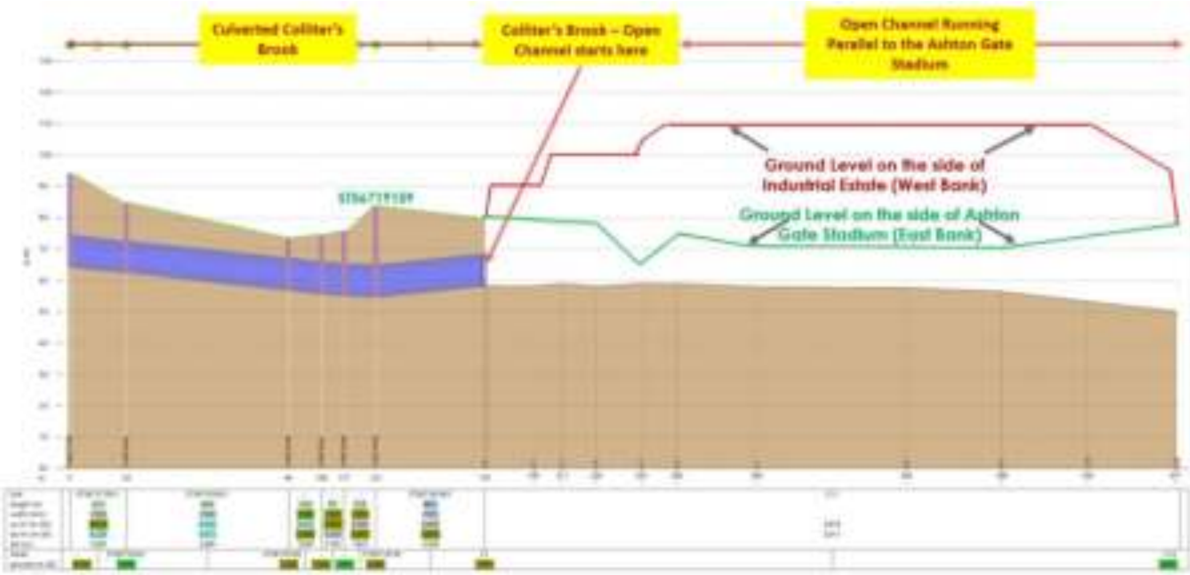


Figure 62: Long-section of the Colliters Brook (Winterstoke Road culvert and open channel section). The flat section and backfall section have high levels of silt and debris which further reduces the capacity of the watercourse.

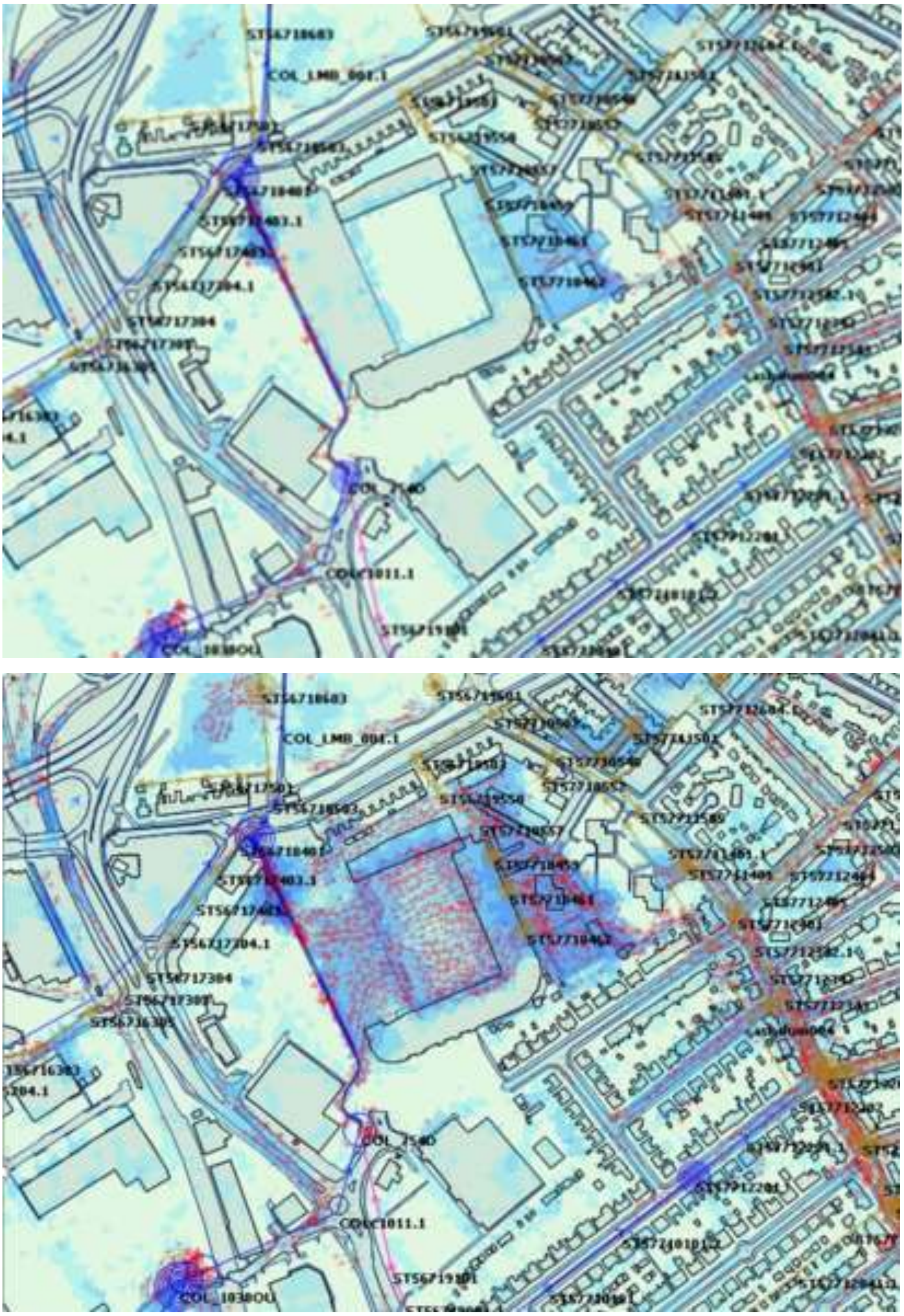


Figure 63: Model predictions for 1 in 20 year storm flooding from Colliters Brook for current rainfall (top) and end of century rainfall conditions (bottom).

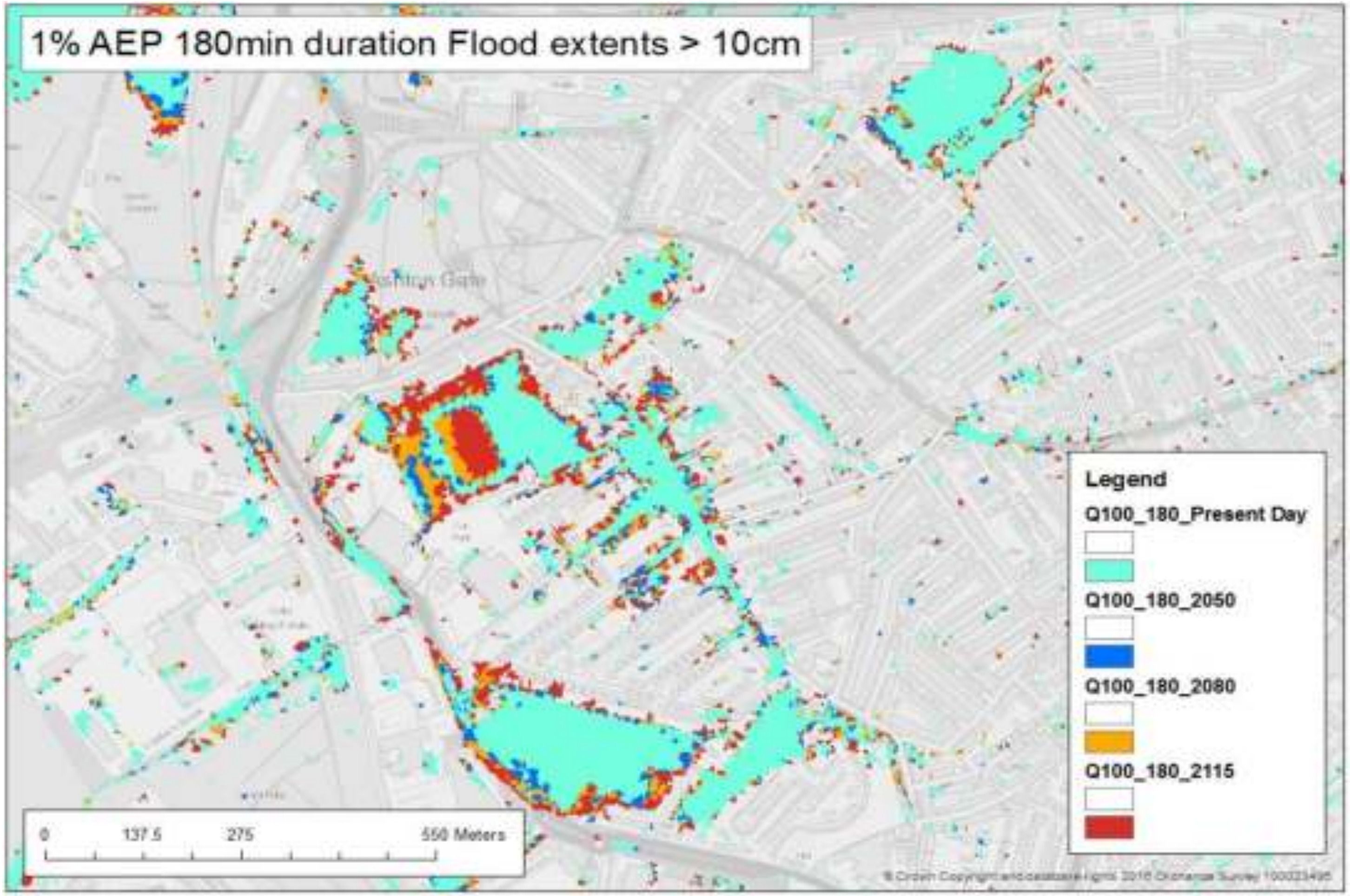


Figure 64: Plan showing flooding extents in Ashton Vale for a 1 in 100 year storm for present day and future climate change rainfall.

Flooding from the Combined Sewer System

Within the Ashton Vale study sub-catchment, flooding from the combined sewer system occurs due to two main reasons:

- Localized inadequacy of pipe capacity
- Backing up of water from Ashton Avenue SPS during storms coinciding with peak tide levels

Localized inadequacy of pipe capacity generally presents a relatively low level of hazard in this sub-catchment but currently occurs relatively frequently (e.g. 1:2 year or 1:5 year RP). Affected areas include Ashton Drive and the Ashton Gate Trading Estate. Flooding tends to be confined to highways but could also impact on 30-40 dwellings and two commercial premises

Flooding as a result of backing up from Ashton Avenue SPS occurs relatively infrequently (e.g. greater than 1:30 year or more) but could be much more serious, potentially affecting over 100 dwellings. The risk will increase with time, primarily due to anticipated rising tide levels, increasing storm severity and catchment growth, as described in Section 3.3.1

In the Ashton Drive area, localized inadequacy of pipe capacity has been significantly exacerbated in recent years by “urban creep” – in particular the paving over of front gardens to provide car parking spaces, as illustrated by Figure 65. This has affected both the combined system and the surface water systems serving this area, increasing the impermeable area by about 30-40% beyond that for which the drainage systems were originally designed. The model output showing resulting flooding is shown in Figure 174 of Document D2.2 (Russo, 2018a).

To achieve the current target flooding performance standard under current rainfall conditions, modelling has identified three key areas where pipe capacity needs to be increased, totaling a pipe upsizing length of approximately 600m in the combined sewer system. In addition to this it will be necessary to seek opportunities to carry out separation within the upstream catchment to offset the existing urban creep. Modelling suggests that a 20% reduction in impermeable area will be necessary to achieve the target flooding standard for current rainfall conditions

Flooding from the Surface Water System and Highway Drainage

Within the Ashton Vale study sub-catchment, flooding from the surface water sewer system occurs due to two main reasons:

- Localized inadequacy of pipe capacity
- Backing up from the tidally affected Colliters Brook
- Backing up from tidal River Avon (minor SW sewer systems and highway drainage

The only large surface water system in the sub-catchment out falls to the Colliters Brook; flooding from this is occurs in Ashton Drive and Winterstoke Road at a frequency of roughly 1:10 year RP, mainly affecting highways. This frequency is anticipated to increase to between 1:2 and 1:5 year RP by end of century.

Small surface water systems (including highway drainage) have not been modelled but these would be affected by increasing tide levels; none of these are currently reported to flood and all are fitted with tide flaps.

Figure 65: Illustrating "urban creep" in the catchment due to paving of front gardens for car parking.

Flooding due to Surface Ponding

The surface terrain data and 2D modelling have highlighted numerous small areas within the catchment which are susceptible to surface ponding due to flow being unable to drain away adequately because of inadequate provision or location of gully inlets. Depths of flooding are small (generally <0.3m) and present a nuisance rather than a flooding hazard. These could be remedied by provision of additional gullies and small extensions to the surface water system where necessary.

3.3.2 Adaptation strategies, measures and design criteria

Flooding from Colliters Brook

Issue

Flooding from open channel section of Colliters Brook adjacent to Ashton Gate football stadium; estimated frequency 1 in 5 year (present day) increasing to 1 in 1 year by end of century under BAU

Target Performance Standard

Avoidance of flooding from the watercourse for a 1 in 100 year RP (AEP 1%)

Outline of Solution

- **Regrading and widening of the Colliters Brook and provision of higher flood walls to contain flows within channel**.
  - This could be tied in with the proposed redevelopment of the industrial area on the west (left) bank of the Colliters Brook – see below
  - Would also include localized raising of walls to contain flood flows within channel

Plus

Either

- **New surface water (land drainage) pumping station (preferred option**)
  - Located alongside Ashton Avenue SPS
  - Indicative capacity of approx. 3.5 to 4.0 m^3/s taking surface water flows in the Colliters Brook.
  - Could be a screw pump station lifting flows to a header tank, only operating at times of high tide

Or

- **Additional screening and storm pumping capacity at Ashton Avenue SPS,** plus
- **Reinstatement of syphons and modification of the overflow structure in Winterstoke Road / Smythe Road (surface water to combined sewer bifurcation)**
  - Possibility to include real-time control element to manage flows to ensure the overflow operates only when flows in the open channel reach critical levels to minimize CSO spill frequency at Ashton Avenue SPS

Additional Considerations

The area to the immediate west of the Colliters Brook open channel section has recently been identified for potential redevelopment as an indoor sports complex and arena, plus high-rise housing. If this development goes ahead (possible in a 5 year timeframe) it would provide a valuable opportunity to improve the watercourse at the same time – see Figure 66 and Figure

67 showing the current situation and extracts from the developer's proposals, which are now in the public domain.

Figure 66: Current view and artists' impression taken from development proposal for the area to the west of Colliters Brook.

Figure 67: Artists' impression taken from development proposals for a new indoor stadium and arena, showing a much-widened and improved channel for the Colliters Brook.

Detail of Solution and Performance Achieved

- Regrading and widening of the Colliters Brook and provision of higher flood walls to contain flows within channel.
    - Desilting of 70 m of Colliters Brook culvert under Winterstoke roundabout
    - Reconstruction / upsizing of backfall section of approx. 60 m of culvert under Winterstoke Road (to 1050 mm x 2500 mm and at a gradient of approx. 1:250)

- Regrading and widening of Colliters Brook open channel from Winerstoke Road culvert to Greville Smythe culvert – approx. 296 m of channel of approx. 5.0 m width and 1.2 m depth at an average gradient of approx. 1:600
- 160m of flood walls alongside channel at lowest point
- Full width trash screen and emergency bypass at downstream inlet to culvert
- Planting and landscaping to enhance amenity

If implemented alone, this solution would achieve a flood protection of approximately 1 in 10 year (under present day rainfall) – better than the current arrangement performance (1 in 5 year) but still falling far short of the target performance standard This is because the watercourse would not have a free outfall and flows would back up during high tide conditions. The enlarged and regraded channel section would thus form temporary storage to contain flows until tide levels recede, but this would be compromised in time by rising sea levels under climate change scenarios. Tidal backing up would also not be desirable for the improved and more visible channel from an amenity point of view.

- **New surface water (land drainage) pumping station**
  - Potentially located on open ground alongside Ashton Avenue SPS
  - Flow diversion chamber to direct stream flow to pumping station at times of high tide
  - Screw-pumping station – duty / assist/ assist, nominal total capacity 3.6 m^3/s, discharging to header structure above Highest Astronomical Tide level at end of century
  - New outfall and head wall for pumped flows
  - Control penstocks
  - Electricity supply, standby generator, telemetry and controls
  - Access road and secure compound (could be extension of existing Ashton Avenue SPS site)
  - Modification / raising of the flow diversion structure at Winterstoke Road (this would become redundant but could be retained for emergency use or to divert flows during maintenance of the downstream culvert, channel and surface water pumping station)

By effectively isolating the Colliters Brook from the effects of the tide, and providing adequate stormflow pumping capacity, this solution (in conjunction with the above channel improvements) would achieve the required 1 in 100 year flood protection for both current and end-of-century. Use of a screw pumping station has the advantage of flexibility to manage a range of flows as well as low energy use; furthermore, under low to medium tide conditions, flow would continue to discharge via the gravity outfall, therefore overall energy use would be relatively low. The pumping station could be designed such that additional pumping capacity can be added in response to climate change or catchment growth

Provision of a land drainage pumping station has the additional advantage that it would reduce the stream / surface water diverted to Ashton Avenue SPS during storms, typically by up to 1,800 l/s during a 1 in 30 year storm. Clearly this has both flooding and CSO benefits for the combined sewer system, releases capacity in the network and reduces energy use in pumping and treatment. It is also in line with combined sewer separation objectives and would reduce the annual average discharge of combined sewage by roughly 260,000m^3/annum.

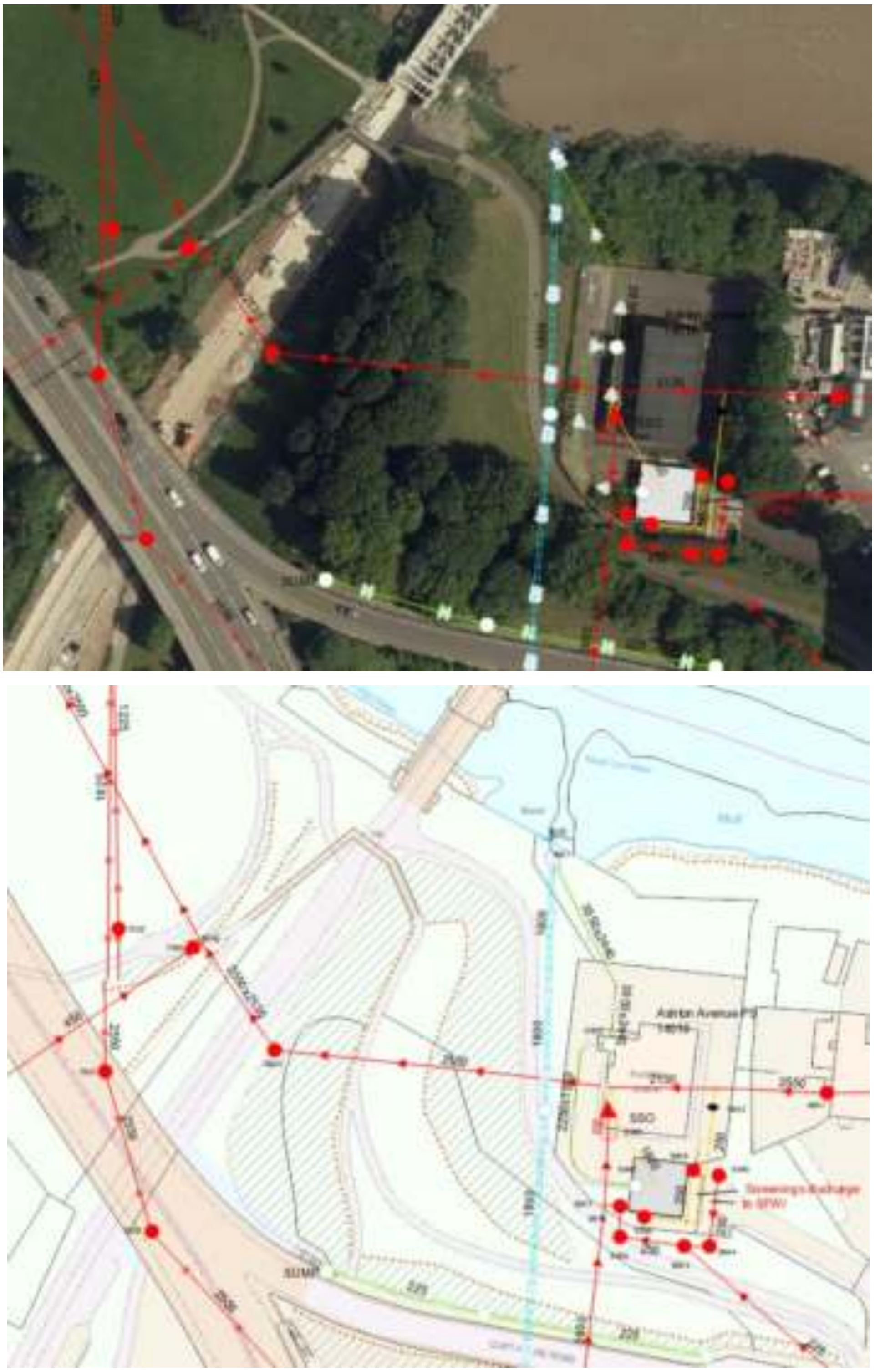


Figure 68: Potential location of surface water pumping station for the Colliters Brook, on open land alongside Ashton Avenue SPS.

Flooding from the Combined Sewer System

Issue

Flooding from combined system in Ashton Drive, Gores Marsh Park and Ashton Gate Trading Estate; current estimated frequency 1 in 2 year (present day) increasing to 1 in 1 year by end of century under BAU

Target Performance Standard

Avoidance of **external** property flooding from the combined sewer system for a **1 in 20 year** RP storm

Avoidance of **internal** property flooding from the combined sewer system for a **1 in 30 year** RP storm

Outline of Solution

To achieve the target flooding performance standard under current rainfall conditions, modelling has indicated that the following measures will be required:

- Combined sewer upsizing in three key areas to increase capacity, totaling approximately 600m of sewer upsizing in roads and gardens.
- Surface water separation to partially offset the effects of urban creep. Modelling indicates that a 20% reduction in impermeable area will be necessary to achieve the target flooding standard for current rainfall conditions. If no separation is achievable then roughly 2,100m of sewer upsizing would be necessary to achieve the same performance

To achieve the target flooding performance standard under 2110 rainfall conditions, modelling has indicated that the following measures will be required:

- Combined sewer upsizing in three key areas to increase capacity, totaling approximately 1100m of sewer upsizing in roads and gardens.
- Surface water separation to partially offset the effects of urban creep. Modelling suggests that at least a 35% reduction in impermeable area will be necessary to achieve the target flooding standard in conjunction with the above upsizing.

Issue

Flooding from combined system due to backing up from Ashton Avenue SPS when extreme storms coincide with extreme high tides; current estimated frequency 1 in 30 year (present day) increasing to 1 in 10 year (or more frequently) by end of century under BAU

Target Performance Standard

Avoidance of **external** property flooding from the combined sewer system for a **1 in 20 year** RP storm

Avoidance of **internal** property flooding from the combined sewer system for a **1 in 30 year** RP storm

Outline of Solution

- Provision of additional storm pumping capacity at Ashton Avenue pumping station, taking the total installed pumping capacity from 9.6 m3/s (current) to 12.1 m^3/s. Provision of additional screening capacity to match storm pumping capacity

Note: As an alternative to providing additional combined sewage pumping capacity to deal with extreme storm and tide conditions at Ashton Avenue SPS the capacity could also be provided in the form of a new surface water (land drainage) pumping station to serve the Colliters Brook, as outlined above. It could be arranged such that when the total (pass-forward + storm) pumping capacity is beaten, any excess flow could overflow to the new surface water pumping station and be pumped out by that. Whilst this alternative would be more expensive overall, it has numerous advantages in that it:

- Also prevents flooding from the Colliters Brook
- Avoids mixing of relatively clean surface water with combined sewage prior to overflow
- Provides additional pumping capacity on the rare occasions that flows exceeding Ashton Avenue SPS without having pumps standing idle for very long periods
- More straightforward to construct and would ensure full continuity of function for the existing Ashton Avenue SPS during the construction period.
- Could be more energy efficient

Flooding from the Surface Water System and Highway Drainage

Issue

Flooding in Ashton Drive and Winterstoke Road at a frequency of roughly 1:10 year RP, mainly affecting highways. This frequency is anticipated to increase to between 1:2 and 1:5 year RP by end of century.

Target Performance Standard

Avoidance of **external** property flooding from the combined sewer system for a **1 in 20 year** RP storm

Avoidance of **internal** property flooding from the combined sewer system for a **1 in 30 year** RP storm

Outline of Solution

- Implementation of the Colliters Brook improvement and land drainage pumping station (see above)
- Upsizing of approximately 250m of surface water sewer in highways and gardens
- Reduction in impervious area connected to surface water system by 20% to offset urban creep by implementation of SUDS such as:
    - tree pit and soakaway systems to replace gullies connected to sewerage system – roughly 25 installations over 1800m of highway
    - Vegetated swales
    - Permeable pavements for on-road parking areas

Some examples of suitable techniques successfully implemented in similar areas are shown below.

Figure 69: Potential SUDS methods for reduction of impermeable area in Ashton Vale.

Flooding due to Surface Ponding

Issue
Approximately 15 localized areas which appear subject to ponding due to inadequate gully provision / positioning for storms of 1:5 year or more frequently.

Target Performance Standard
In line with surface water system performance (above)

Outline of Solution
The solution has not been modelled explicitly but it is estimated that it would entail:

- Approximately 20 additional gully inlets or SuDS features to intercept flows associated connecting pipework to the nearest surface water drainage system (or combined system if there is no SW system nearby). Total length of pipework estimated to be 300 m of 150mm diameter, mainly in highway

3.3.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

The Bristol SWMP model for the Ashton Catchment was refined to aid the understanding of the interactions between the Colliter's Brook watercourse and Wessex Water drainage network present and serving the área. An improved representation of the model was informed by previously modelled structures being included and aided with advanced surveying to give enhanced understanding of the connectivity of these water systems. The options testing within the Ashton catchment comprised a series of flood alleviations that have subsequently been developed and tested. The results of which are summarized below.

Upgrade Storm Capacity at Aston Avenue Pumping Station

The pumped overflow capacity of 7.5m^3/s if raised to 10m^3/s causes a reduction in the peak water level in the upstream network in the lower order storm events. For the 1 in 30-year event, a reduction immediately upstream of the SPS is still evident but the 1 in 100-year event still exceeds the pipe system and flooding occurs. This is to be expected though since sewers are designed in accordance with Sewers for Adoption standards that specify containing up to the 1 in 30 year event and not beyond. It appears surface water flooding will only be reduced considerably enough in combination with other solution remedies. See Figure 70 and Figure 71, cross sections of the piped network under the 1 in 30 and 1 in 100 year events respectively.

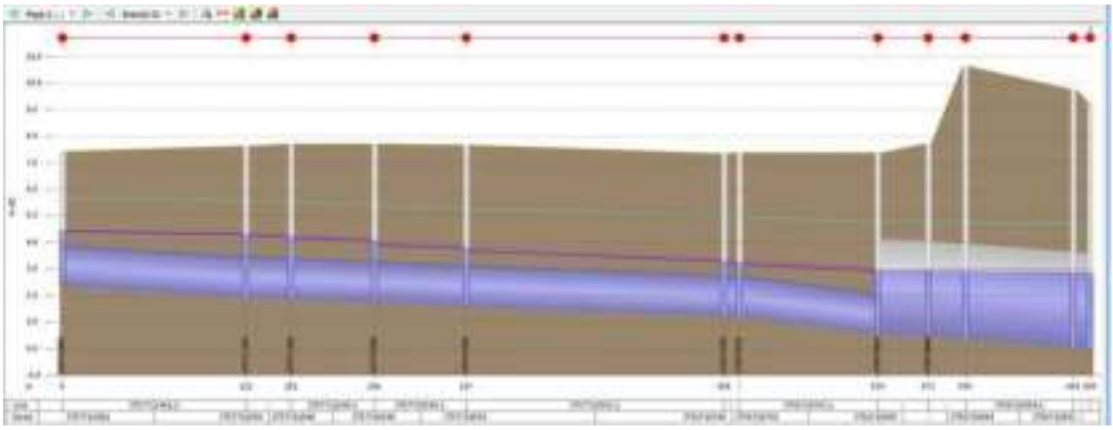


Figure 70: 1 in 30 year pluvial flood event reflected in long section view of the underground piped sewer system at Ashton Gate.

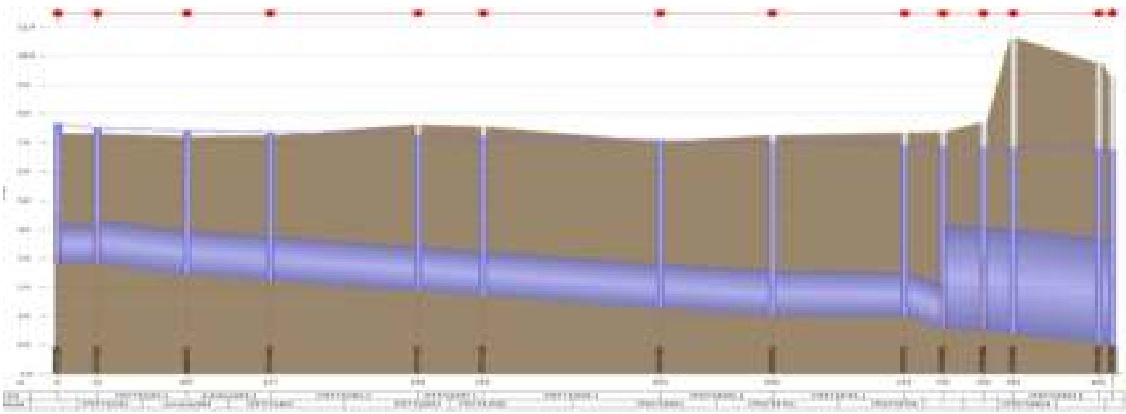


Figure 71: 1 in 100 year pluvial flood event reflected in long section view the underground piped sewer system at Ashton Gate.

Impermeable Area Reduction

Around the Ashton area there has been a noticeable paving over of green space producing a resultant increase in surface water runoff. This is in an area already identified as subjected to a higher risk of surface water flooding. To counteract these impacts a greening of streets through implementing SuDS measures was scoped out as a further possible intervention. This was modelled by reducing the runoff coefficient by 20% which in reality could be achieved by utilizing a multiude of options such a permeable paving, bioretention planters and other similar means to reduce the amount of rainwater entering the sewer network. In implementing this a 5-10mm and 10-15mm reduction in surface water flood depths are notable for the 1 in 30 and 100-year events respectively. Figure 72 shows the designated area considered in the model through which this benefit could be realized.

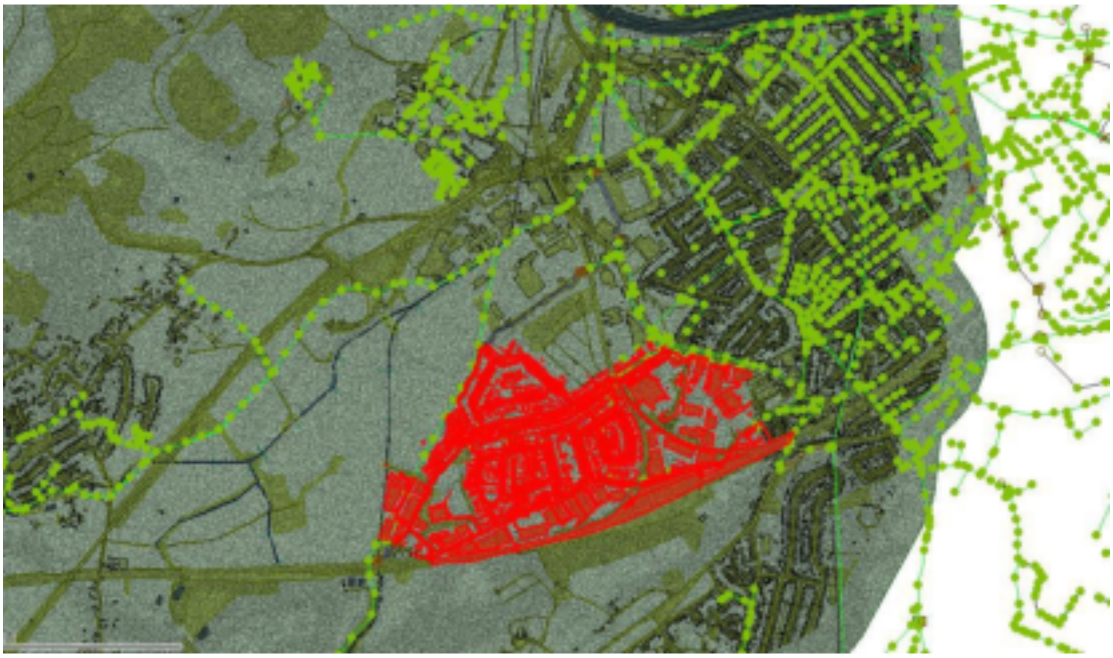


Figure 72: Impermeable area reduction in Ashton.

Again this option alone does not produce a significant enough reduction in the levels of surface water flooding expected in the Ashton area when considering the projected impacts of climate change. For smaller magnitude rainfall events the benefits will sooner be noticed however and would contribute towards an overall flood mitigation for the area.

Re-grade Colliters Brook at Wedlock Way

The irregular gradient of the culverted section of the Colliter's Brook and pipe invert levels at this location may impact on the flow within the Wessex Water surface water network. The discharge into the combined network could be reduced by re-grading the downstream section of the culvert and the open channel section. Figure x below illustrates a possible change that could be made to this stretch of the Colliter's Brook and was modelled to consider its potential impacts.

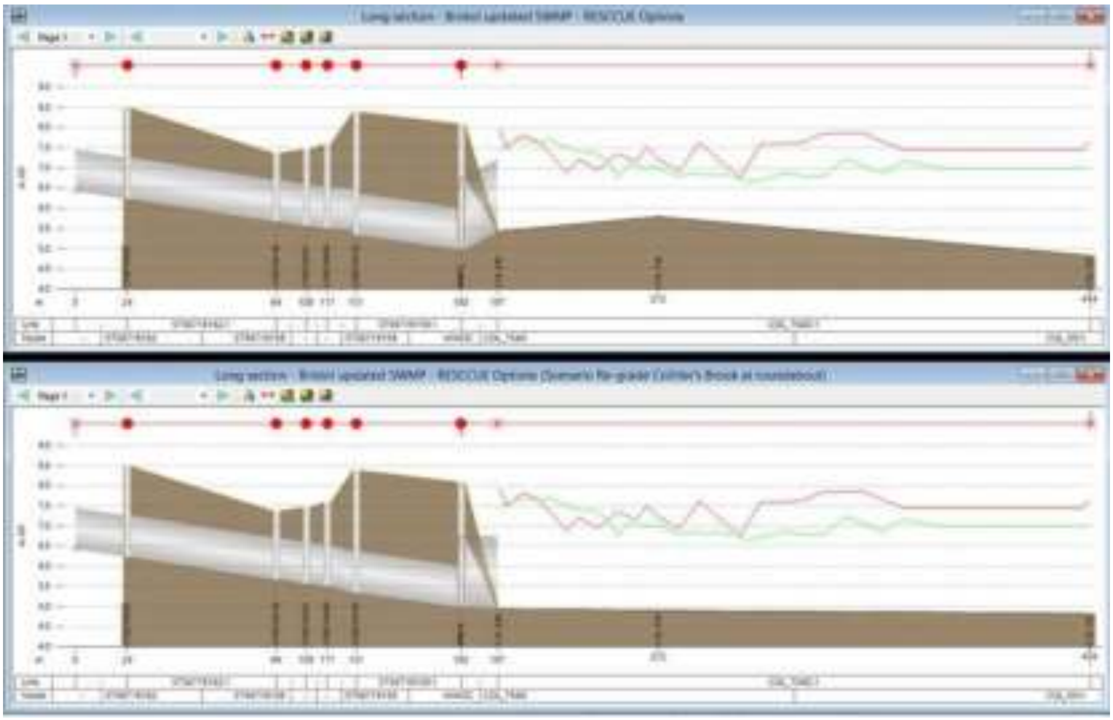


Figure 73: Existing culvert long section and a potential re-grading option on the Colliter's Brook.

The hopes that this option would make significant improvements in flow conveyance along this section of the watercourse were not apparent however. The downstream peak water levels and discharge rates calculated through the model were negligible, producing less than a 1% reduction in regards of these aspects when considering the 1 in 10 year event.

<u>Increase weir level at Smyth Road Bifurcation</u>

The Smyth Road Bifurcation structure diverts flows to the combined network in Duckmoor Road, an area that has previously suffered high levels of fluvial and pluvial flooding. A high-level lateral weir and flap valve at the downstream end of the chamber helps prevent flows backing up in the Colliter's Brook. Raising of the weir level by 300mm in the model was applied with the aim to investigate the potential of reducing the spill frequency and subsequently flood volumes entering the eastern part of the network, leading to the flood prone vicinity. The reduction in spill frequency was however not of huge benefit though in that the flood water volumes did not alter significantly.

<u>Redevelopment of Ashton Gate Stadium area</u>

The chance to increase conveyance and provide flood attenuation storage within the Colliter's Brook open channel section was investigated through modelling a widening and formalising of the banks of the open river section by Ashton Gate stadium. The proposal is displayed in Figure 74 below.

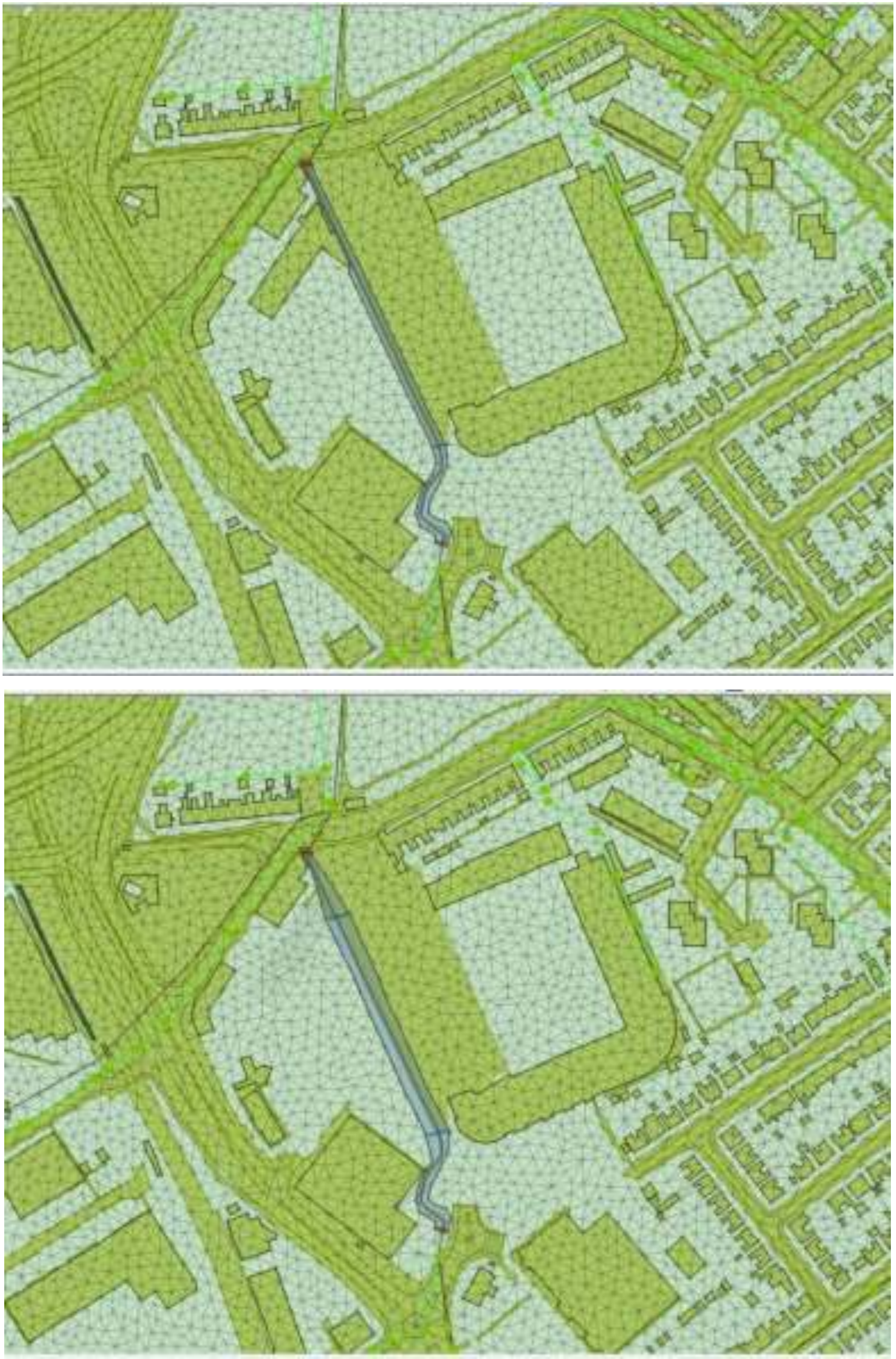


Figure 74: Showing the existing and proposed open channel sections of the Colliter's Brook adjacent to Ashton Gate stadium.

A small amount of additional flood storage area would be available at this location providing benefit for the lower order return period flood events.

In conclusion it is clear that a combination of adaptation strategies operating in unison are necessary in the Ashton area and that infrastructure upgrades as well as source control of surface water are essential components of this.

3.4 River System

3.4.1 Introduction and summary of climate hazards for the river system

The Central Area Flood Risk Assessment (CAFRA) model assessed the risk from joint probability flood events in the centre of Bristol whilst accounting for the benefits also derived from existing flood defenses. This considered combinations of tidal and fluvial sources of flooding of varying magnitudes on the tidal River Avon and the lower reaches of its tributaries. The CAFRA computer software model was produced comprising hydraulic and hydrological modelling. A 1D river network was represented using ISIS software and a 2D ground surface in TuFLOW software. The hydrology calculations include an allowance for climate change for two epochs for the 2060s and 2110s periods. This accounted for the projected effect of sea level rise on high spring tides and for heightened river flows. The outcome of the analysis assessed that tidal flooding poses the greatest risk to the central area of Bristol and this risk will become far more significant in coming years. Further model iterations updated the representation of the ground surface and changes in climate change projections. Outputs from the model are available in GIS format that show the depth, level in mAOD, velocity and hazard rating across a number of return period events.

The Avonmouth Severnside area in the west of the city lies adjacent to the Severn Estuary and is directly subjected to these tidal influences and the effects of its 14m tidal range. The Level 2 Strategic Flood Risk Assessment (SFRA) model covering this region assessed the flood risk from a combination of interconnected tidal and fluvial sources. The tidal element was represented in high spring tides and fluvial component representing the series of drainage ditches, known as the Avonmouth Rhine network, that serve this low lying tidal area. Model iterations have accounted for updates to the hydrological input, wave impact analysis and climate change when available and where required.

Tide gauges at Cumberland Basin and Bedminster Bridge in central Bristol and at Avonmouth by the Severn Estuary have enabled some model checks and calibration through the analysis of high tide data. The high tide monitoring apparatus at these localities utlises radar sensor-type water level measurement gauges with telemetry which has helped calibrate the above river and tidal flood models. Tidal flood levels measured at the Severn Estuary and tidal River Avon have provided some verification of the model outputs. Further information about the flood models, their validation and main features is provided in greater detail in Deliverable 2.2 (Russo, 2018a).

The risk from joint probability tidal and fluvial flooding in Avonmouth and the central Bristol area in the present day is already deemed as significant, as is indicated in the accompanying flood mapping illustrated in figures below. These figures demonstrate the predicted flood extent outlines and also associated flood hazard ratings.

Figure 75. Predicted flood extent from a 0.5% Annual Exceedance Probability (AEP) tidal flood event in central Bristol.

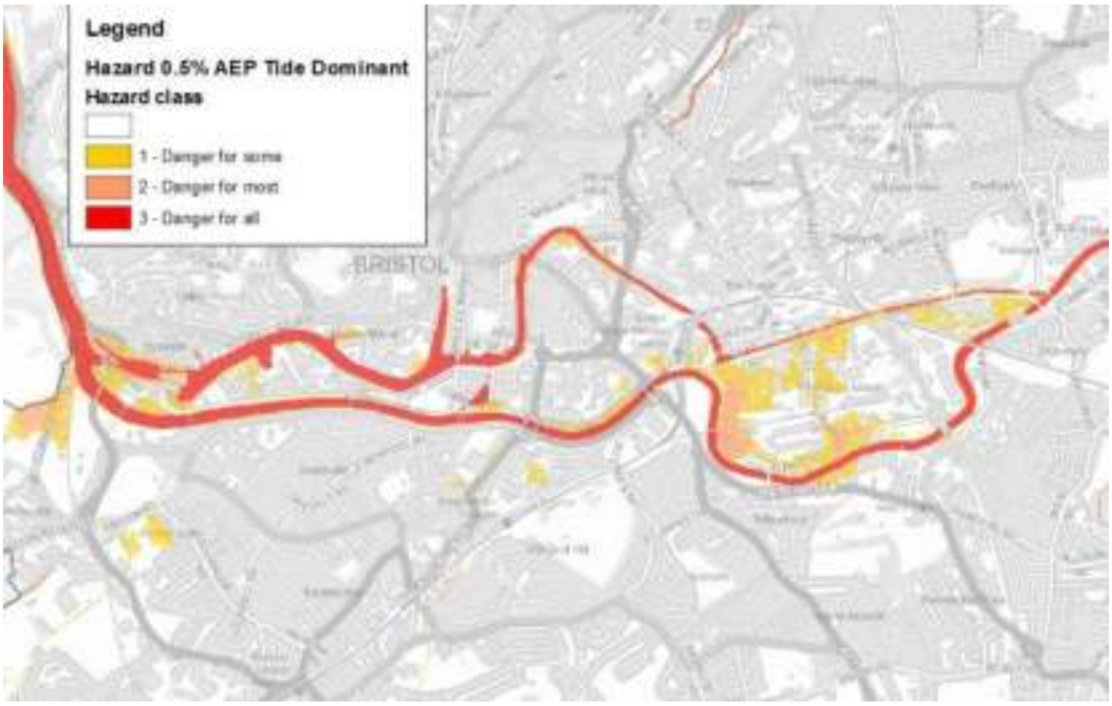


Figure 76. City Centre Flood Hazard Map for the 0.5% AEP tidal flood event.

Figure 77. Predicted flood extent from a 0.5% AEP tidal flood event at Avonmouth.

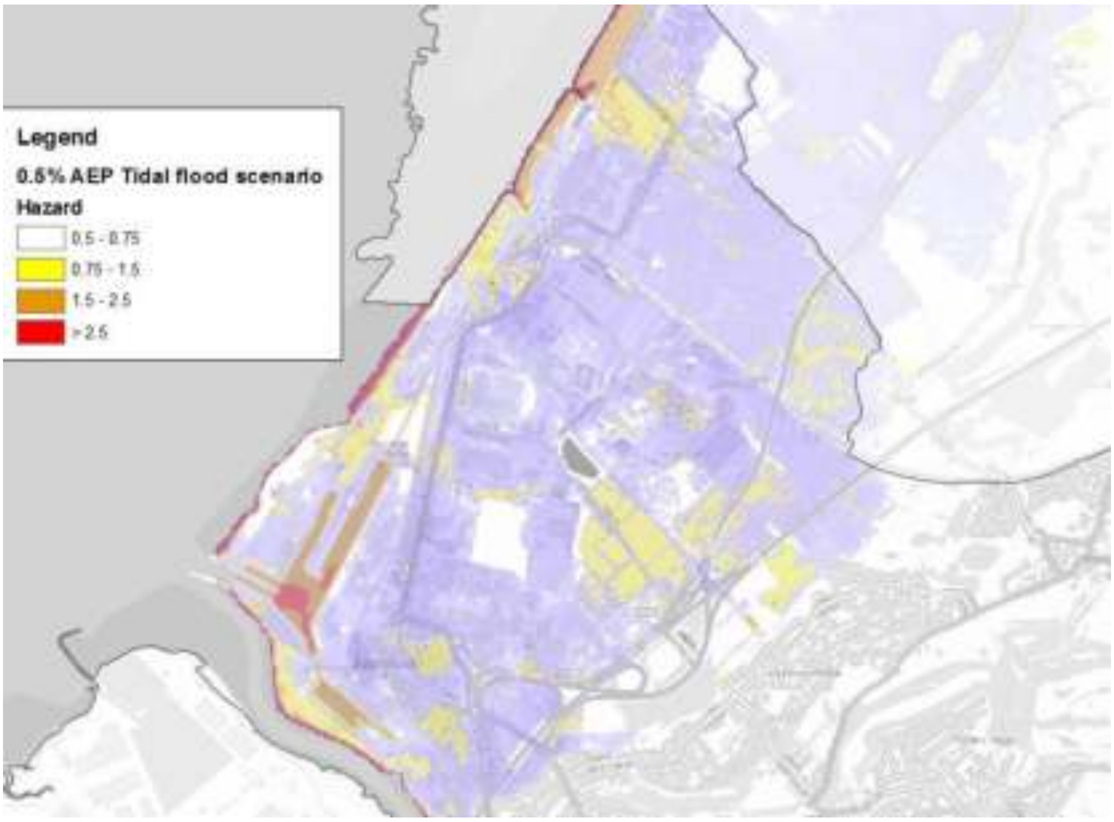


Figure 78. Avonmouth Flood Hazard Map for the 0.5% AEP tidal flood event.

Climate change impacts in the future are predicted to increase the anticipated flood extents and indeed the flood hazard rating too. Flood modelling conducted with a climatic uplift accounting for sea level rise as well as additional river fluvial flows is demonstrated in figures w-z that follow. The Deliverable 2.3 document elaborates on the scientific research and analysis behind this with provision of much further detail and information (Russo, 2019). To highlight the main impact and summarize the implications; the estimated flood levels are expected to increase gradually in the more immediate future but then rapidly towards the turn of the century making for an approximately one meter rise by the year 2115.

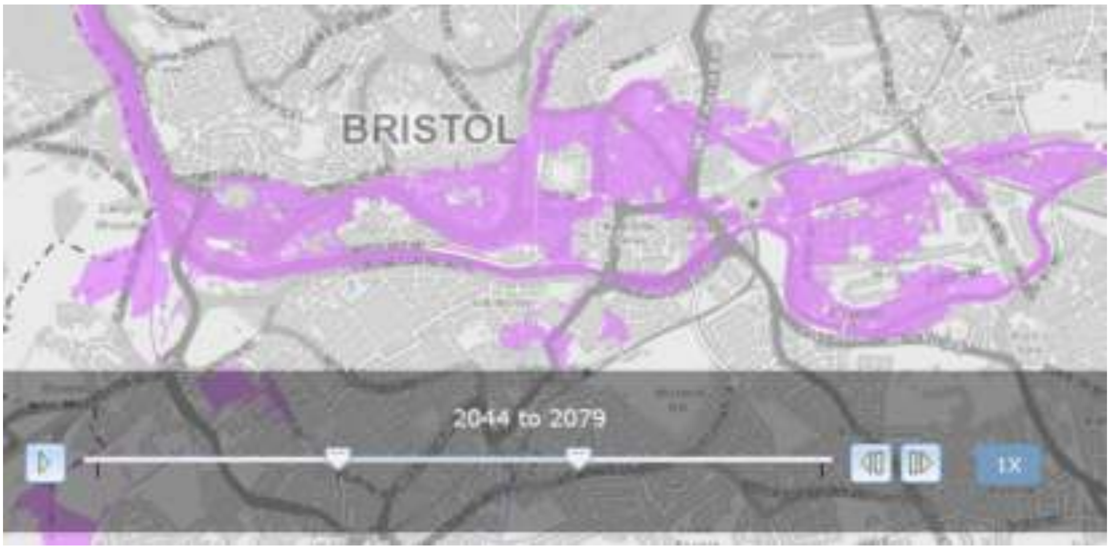


Figure 79: Predicted flood extent from a 0.5% Annual Exceedance Probability tidal event from 2044-2079.

Figure 80: Predicted flood extent from a 0.5% Annual Exceedance Probability tidal event 2079-2115.

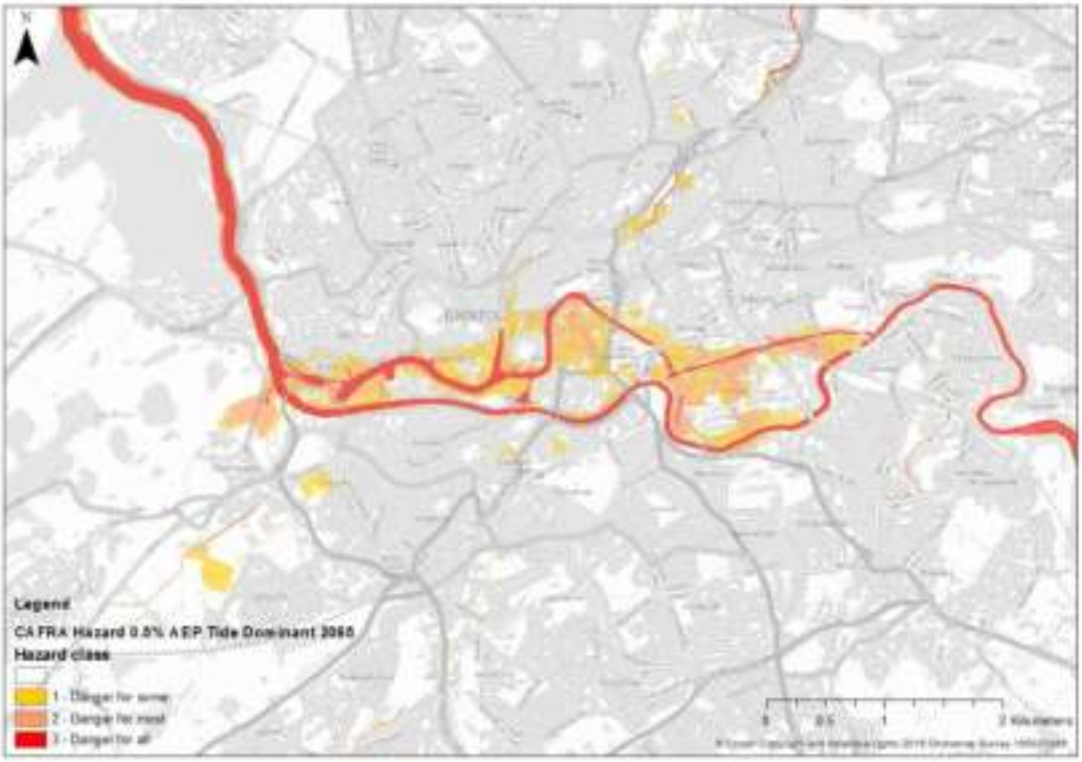


Figure 81: 2065 tidal flood hazard.

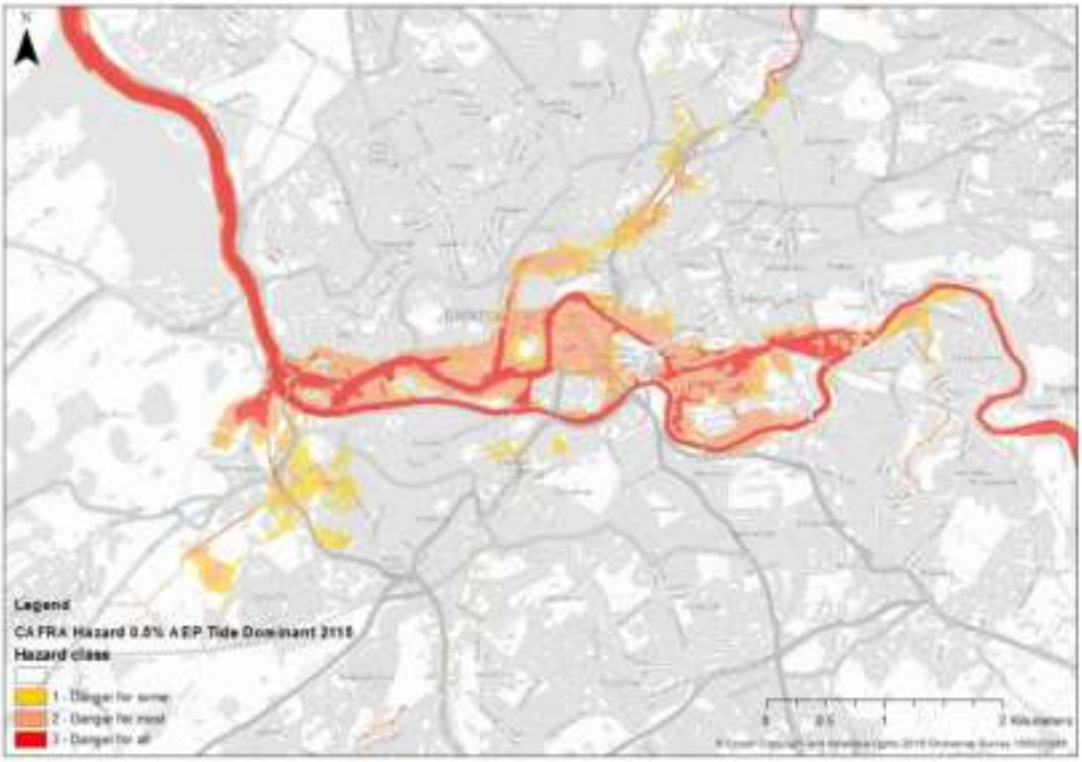


Figure 82: 2115 tidal flood hazard.

The flood risk in the city centre associated with the flood mapping portrayed above make it seem unjustifiable to do nothing in response to the apparent catastrophic consequences attributed to this hazard. That said, in terms of justifying spend on appropriate mitigations optioneering must scope out the most beneficial return on cost benefit ratio for implementing adaptation strategies which is explained in coming sections.

The flood implications in the Avonmouth area raise similarly with climate change and analysis of this and the scoping of reasonable and practical flood management actions to react in enough time to this future propogated risk has been undertaken in the Avonmouth and Severnside Ecology Mitigation and Flood Defence Scheme (ASEA flood defence scheme). The modelling of adaptation strategies for this area has therefore not been taken further. A description of the means in which appropriate flood resistance measures at Avonmouth were assessed is provided in sections 3.4.2 and 3.3.3 that follow though (Evans, 2019).

3.4.2 Adaptation strategies, measures and design criteria

Addressing the low spots along the riverside of the tidal River Avon is designed to eliminate the tidal ingress of flood waters during high spring tides. The glass wall effect (unlimited riverside wall height extensions to lower lying positions) has been applied in order to achieve this and in order to equate the reduced risk of tidal flooding in the Bristol central area. A visualization of this idea is shown in Figure 83.

Figure 83: Visualization of where riverside flood defence walls would be positioned at a point on the tidal River Avon.

An example of where and how this has been applied elsewhere is illustrated in Figure 84 below that highlights the range of different engineered or soft landscaped solutions in and around the Avonmouth area to reduce tidal flooding in that area.

Figure 84. ASEA flood defence scheme proposals schematic overview.

It is seen from the above schematic that due to the long stretch of water and varying terrain, land cover and ground conditions that a variation of flood defenses is the only appropriate alternative. This is a similar case for the tidal River Avon since this is affected by the same tidal influences, although this is even more complex and extensive particularly given the greater variability in land use cover, ownership and related variety of necessary engineered solutions. Existing riverside low spots act as flow paths enabling flood routing. The flood mapping shows that the south of the river is less prone to tidal flooding than the north side due to its higher elevations. The design criterion in the UK is typically providing protection against the 0.5% AEP tidal flood event and/or the 0.1% AEP fluvial flood event. In 2115 an estimated flood water level of 10.1m AOD would require a design flood wall of 10.3 m AOD (inclusive of a 200 m freeboard). Several kilometers of flood defences between 1.4-1.8 m high would be required to achieve this long term flood reduction objective. A variation of flood walls such as reinforced concrete cantilever walls and sheet piled walls would be sought out for critical locations where defences are lowest along the River Avon New Cut and at low points along the harbour side. Flood defences would be required in central Bristol at key locations including; Entrance Lock, Cumberland Road, Commercial Road, Clarence Road, Cattle Market Road, Totterdown / St. Phillips and Netham. Establishing the exact requirements and completing the detailed design is outside the time range and scope of the RESCCUE project however the initial steps have been undertaken to quantify the cost benefits derived from implementing such flood mitigations which will assist to inform these essential future project works. The following section captures this in further detail.

3.4.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

Treating the complete removal of Flood Zone 3 (extent of the 0.5% AEP / 1 in 200 year return period tidal flood event) as the solution to the central area flooding problem for modelling purposes will be applied. Bearing in consideration that heightened flood defenses will be filling the low spots, although not yet predefined in each individual case or locality for modeling purposes the total eradication of flooding within this predetermined zone can been assessed in the monetary (or otherwise) gains it achieves. The design flood level that will be used is defined as 9.4mAOD for 2080 and 10.1mAOD for 2115. In the current day around 1000 properties in central Bristol are at risk from a 0.5% AEP tidal flood event. With the effects of sea level rise this will rise to 3700 properties by 2115. The vulnerable areas include the Bristol Enterprise Zone and city centre which is of strategic importance to South West England. Direct asset damages as well as intangible damages and benefits can be quantified like traffic disruption, mental and physical health impacts.

Removing the flooded areas completely from the flood outlines previously determined helps to establish the benefits derived from a range of different aspects. Not only cost analysis from quantifying damages previously incurred and subsequently avoided but also what the improvements on the running of critical services that are functioning within these areas. A suite of damages assessments have been undertaken to estimate the financial impact of flooding in the Avonmouth area also over an 80 year period which helped justify the ASEA flood defense scheme works and gain funding. This entails the comparable cost analysis of usual dry weather conditions versus extreme flood conditions, inclusive of climate change impacts. Figure 85 and Figure 86 illustrate this concept and proposal and comparison between the two should be modelled.

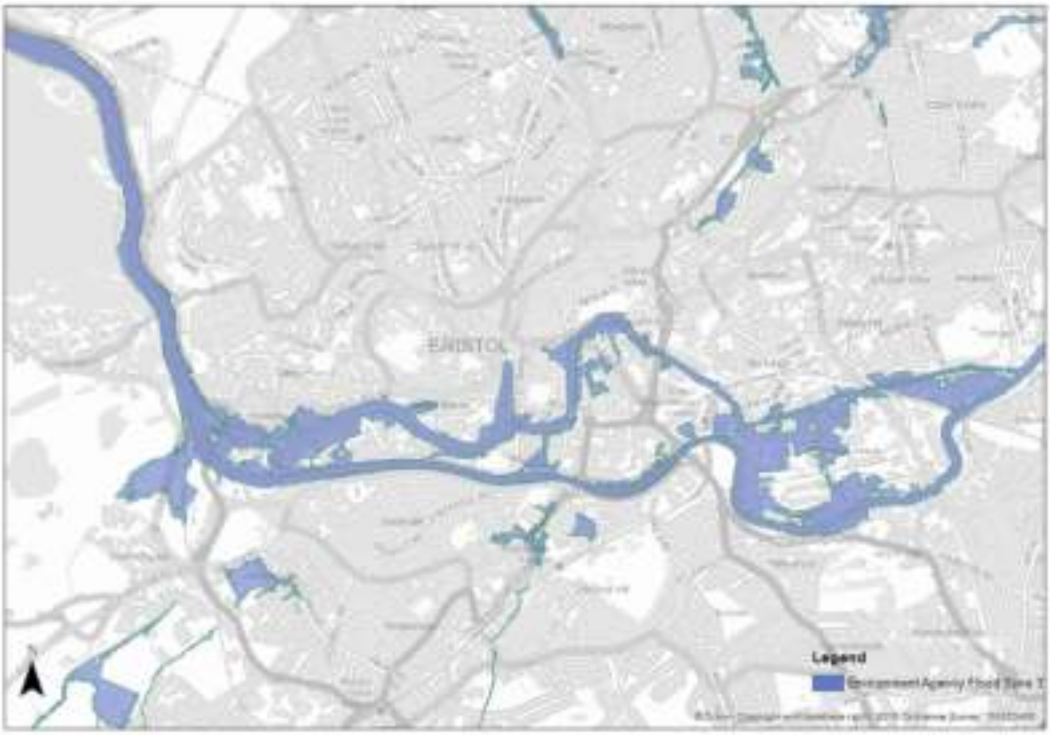


Figure 85: Areas of Flood Zone 3 in central Bristol.

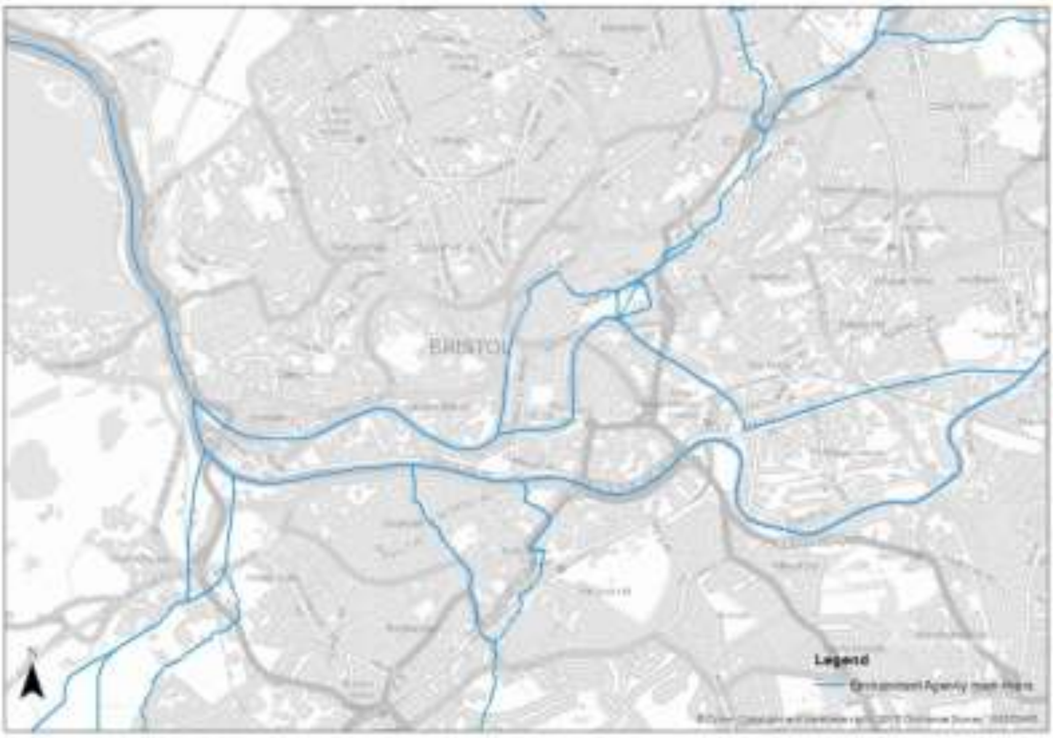


Figure 86: Removal of Flood Zone 3 in central Bristol from adaptation strategy.

Quantifying the damages and cascading effects of the future flood impacts can give not only a monetary value but also the assessment of the functioning of critical services and utilities as well as further environmental implications. These are substantiated in the Work Package 3 deliverable D3.4 which should be referred to for further detailed information. The further evaluation of flood impacts on the Wastewater and Drainage sector, as well as on the Traffic and Energy sectors is contained within D3.6. D3.6 will substantiate the monetary losses and increased costs incurred from flood impacts as well as other intangible benefits and tangible economic impacts to proportionate the value that the effects an extreme tidal flood event would have in central Bristol in the current day and in the future. The costings of riverside flood defense walls must therefore be cost effective in line with the above information to provide enough benefit in order to justify their spend.

3.5 Traffic sector

3.5.1 Introduction and summary of specific climate hazards for the urban drainage sector

The Bristol case study is utilizing a loosely coupled modelling approach to analyze the impacts of flooding on traffic flows. Within this approach flood model outputs generated for Baseline and Business As Usual (BAU) events are used to determine the magnitude of hazards posed to the flow of traffic along the road network. This hazard data can then be translated and utilized as inputs within a micro-scale traffic model such as the Simulated Urban Mobility Model (SUMO) (Lopez *et al.*, 2018) as a means of quantifying the impacts to traffic flows (Pyatkova, 2019).

As highlighted previously in Deliverable 2.2 (Russo, 2018a), within the traffic model, the hazard inputs are generated via analysis of the maximum flood depths along the road network that have been discretized into three hazard classifications as shown

Table 28.

Table 28: Hazard Parameters based on Maximum Flood Depths (m).

Maximum Depth Parameter (m)	Effect
0 ≤ Depth < 0.1	No Effect
0.1 ≤ Depth < 0.3	Shallow Flooded Road (Reduced Maximum Speed)
0.3 ≥ Depth	Deep Flooded Road (Closed Road Section)

For the traffic modelling within the city of Bristol we are considering 3 return periods for both the Baseline and BAU accordingly. Figure 87 and Figure 88 show the relationship between the numbers of the discretized affected links with respect to the severity (return period) of each of the pluvial rainfall event. Here we observe that, as predicted, that under future climate change predictions the percentage of roads affected by flooding will increase.

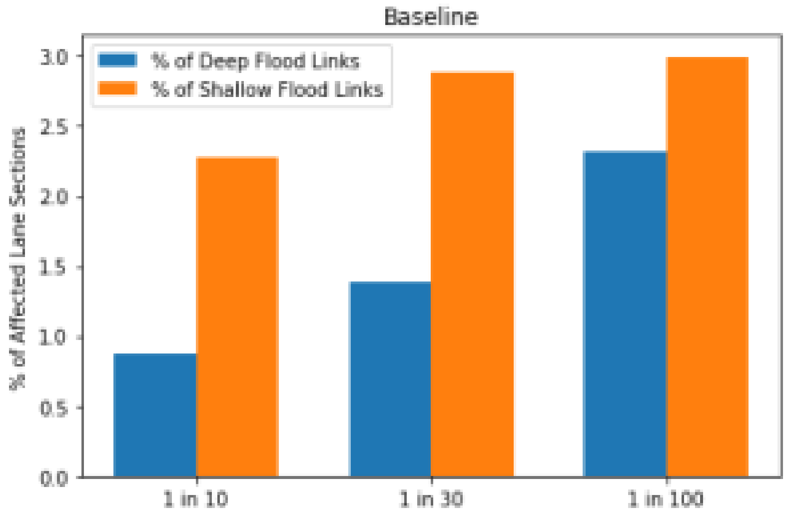


Figure 87: Percentage distribution of discretely flooded links within network (Baseline Scenarios).

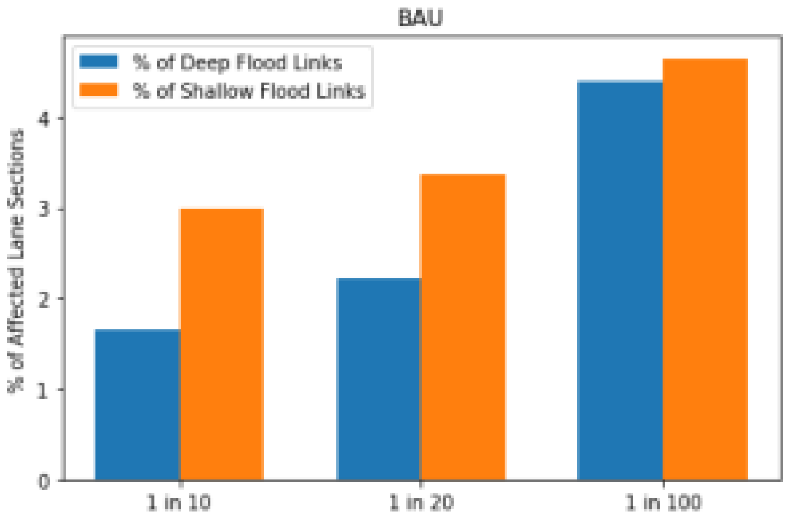


Figure 88: Percentage distribution of discretely flooded links within network (BAU Scenarios).

3.5.2 Adaptation strategies, measures and design criteria

As shown in the previous section and also in Deliverable 2.2 (Russo, 2018a), the road network within Bristol is susceptible to disruption from both Fluvial and Pluvial flooding events. In regards to the Fluvial analysis and selected adaptation strategies, the city of Bristol as sought to investigate the incorporation of flood defenses around the river network to prevent flooding for up to 1 in 200 year events (the details of this fluvial modelling were outlined earlier in section 3.3.2). As such, for the focus of adaptation measures for the purpose of traffic modelling/hazard assessment is focused on reducing hazards (and subsequently impacts) pose to traffic from pluvial flooding events using outputs from the Surface Water Management Plan (SWMP).

The topography city of Bristol is bisected by a river that flows east to west though it (Figure 89). Due to this river, traffic flows within the city that move between the northern and southern regions are partially restricted along bridges that form critical components within the road network. For the adaptation measures within Bristol in relation to traffic, we have therefore focused on analyzing the benefits of ensuring these critical components (bridges) within the road network are kept free of flood waters.

Figure 89: Selected study area the Bristol.

3.5.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

Figure 90 shows the immediate chain/workflow of how the Hazard Assessment utilizes inputs from WP1 and WP5 and provides outputs for the impact assessment in WP3. Within this approach climate data from WP1 is used as inputs to generate the flood hazard maps for Baseline and BAU scenarios. Adaptation strategies from WP5 are applied to the hazard outputs to generate revised hazard maps as part of WP2 that will feed into WP3 for the impact assessment.

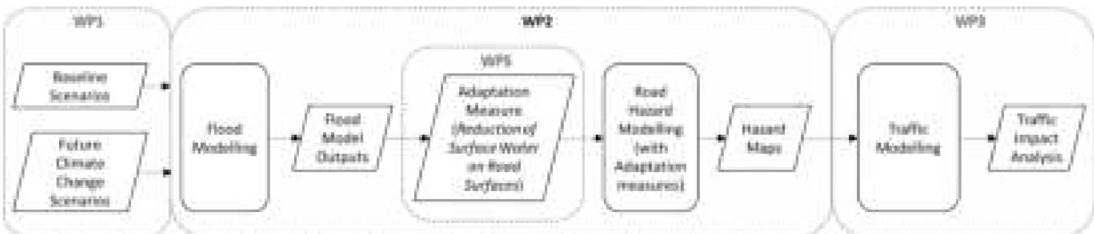


Figure 90. Workflow diagram of incorporation of Adaptation strategies in the analyses

Within the selected study area for Bristol, 111 individual link sections (individual lanes) have been identified that bisect the river network (Figure 91).

Figure 91: Identified bridges within the study area.

Figure 92 shows a visual comparative analysis of the affected bridge features within the study area for different return periods under both Baseline and BAU scenarios. Here we see that even during the more frequent 1 in 10 year events what have been deemed “critical components” of the road network are blocked meaning that significant rerouting of traffic may be required when moving between the north and south regions. Figure 93 and Figure 94 show more clearly the overall effect these flood events could have on the flow of traffic within the network showing that even for the 1 in 10 year event under current baseline conditions ¼ of the identified bridges are effected and in the selected worst case scenario for future climate change predictions ½ of the lanes that cross the river network ae closed.

In summary the hazards posed from pluvial flooding events could have significant impacts in the mobilization of traffic due to flooding of key critical components within the road network. The hazard maps for the various flooding scenarios produced in WP2 with and without the identified bridges will be provided as inputs to the following WP3 for the impact assessment to determine the benefits of ensuring these assets are improved and maintained to keep free of floodwaters.

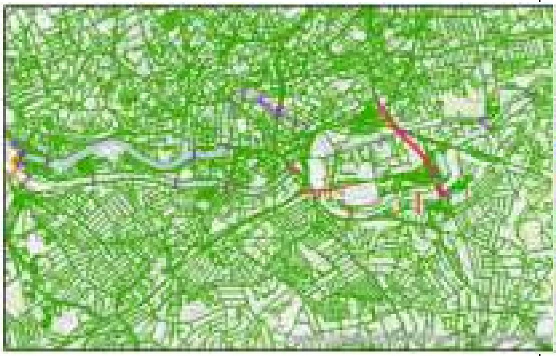
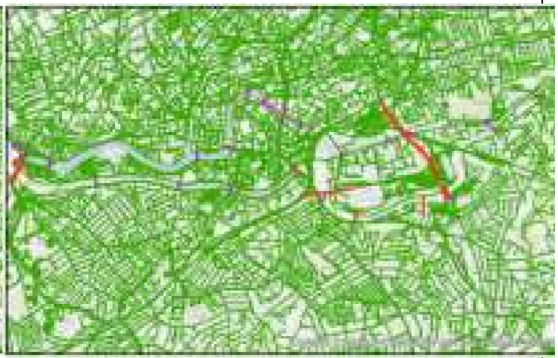
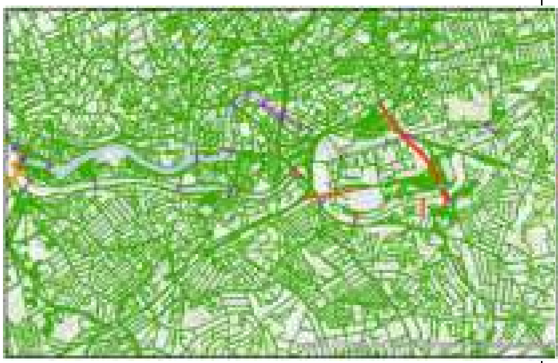
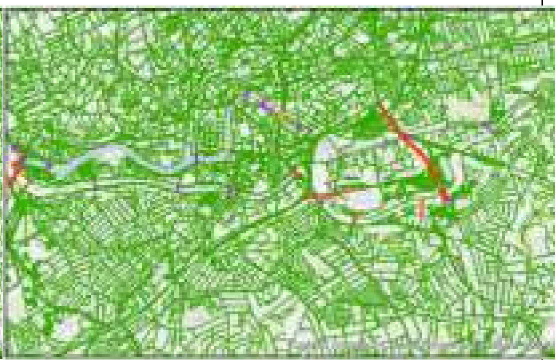
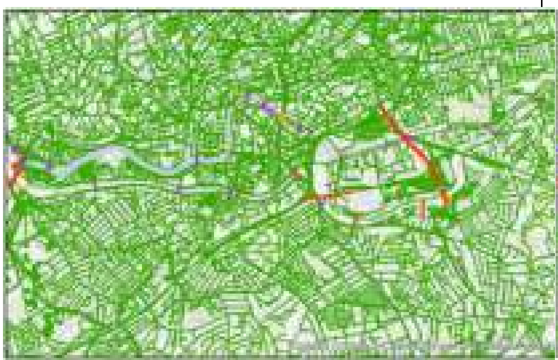
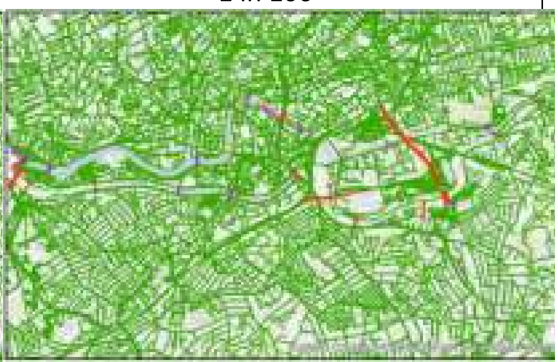
Baseline	BAU
1 in 10	1 in 10
	
1 in 30	1 in 20
	
1in 100	1 in 100
	

Figure 92. Analysis of Flood Hazards posed to traffic along Bridge feature for Baseline and BAU scenarios.

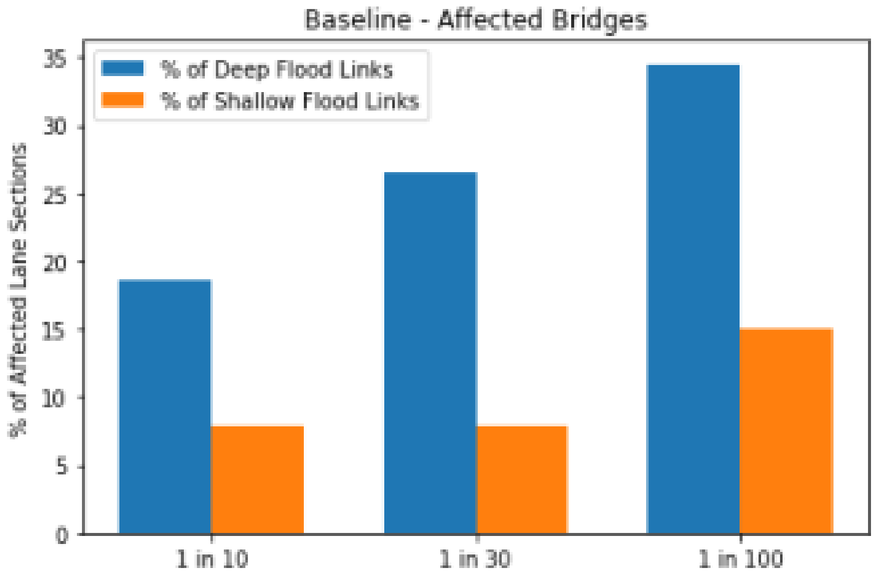


Figure 93: Percentage of Bridges effected by flooding (Baseline).

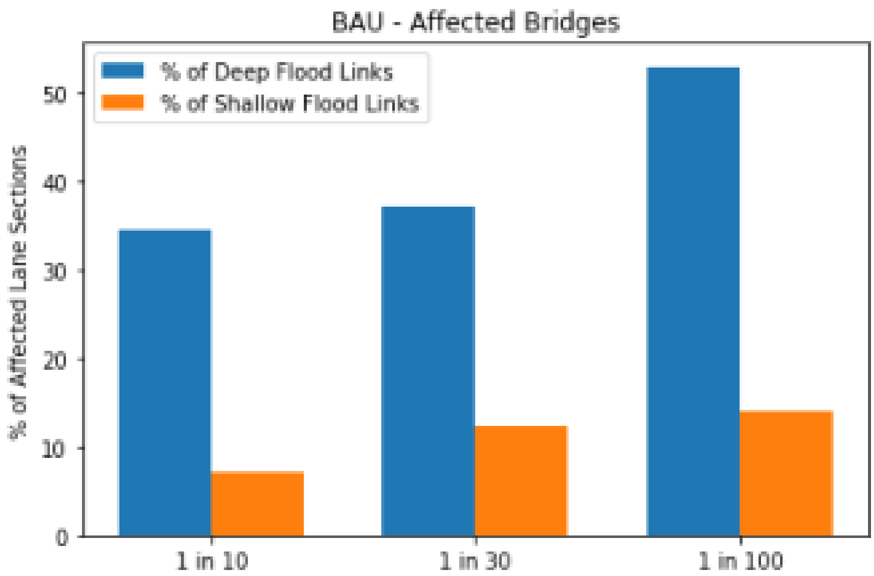


Figure 94: Percentage of Bridges effected by flooding (BAU).

3.6 Electrical sector

Within the central region for Bristol, the adopted adaptation strategy for investigation in relation to reduced impacts on the energy sector are based around reducing the vulnerability of key infrastructures as opposed to hazard reductions. Figure 95 and Figure 96 show examples the exposure of substations within Bristol to Pluvial and Fluvial + Tidal flood events respectively for current scenarios. Within the scope of this deliverable the hazards and subsequent levels of exposure to substations remains the same and the details as to the changes in the impacts via reducing their vulnerability are outlined within the Impact assessment in Deliverables D3.5 and D3.6.

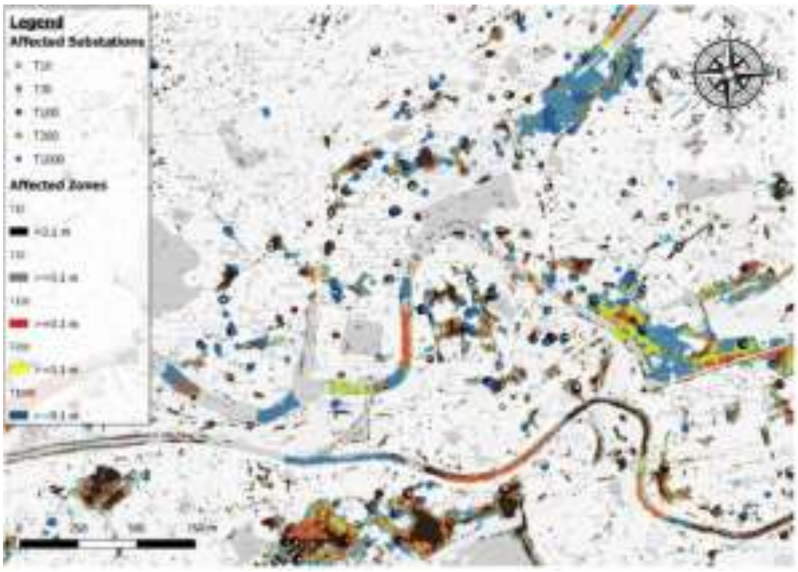


Figure 95: Exposure of substations to various return periods for pluvial flood events.

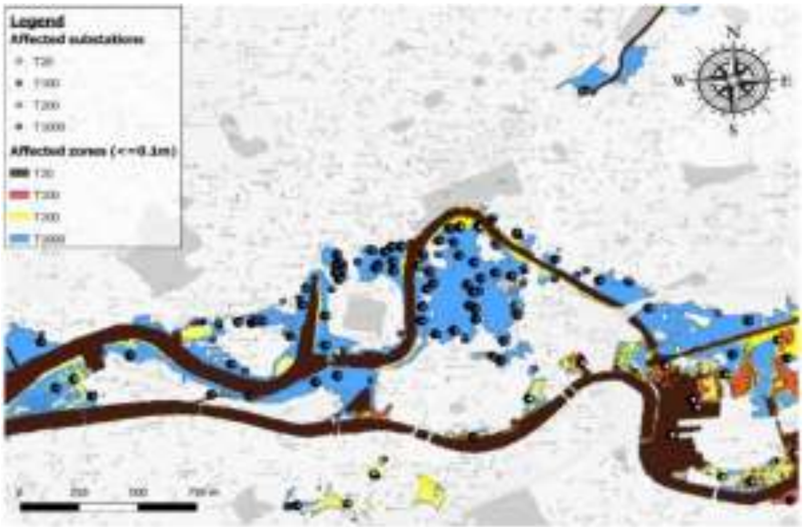


Figure 96: Exposure of substations to various return periods for pluvial flood events..

3.7 Conclusions about adaptation strategies implementation for Bristol Research Site

The city of Bristol is exposed to flooding from both Pluvial and Fluvial combined with Tidal flooding events and the effects of these are only going to get worse due to a combination of both climate change and sea level rises.

A number of approaches for mitigating the effects of climate change and sea level rises have been investigated by the city of Bristol within the scope of RESCCUE and can be divided into two main categories:

1. Reduce Impacts via reduction of Hazards
2. Reduce impacts via reduction of infrastructure vulnerabilities

With one of the main predicted drivers of losses for the city being as a result of Fluvial and Tidal flooding (as outlined in D3.4) one of the identified strategies outlined in this document is the incorporation of flood defenses along the river network. These defenses would in effect mitigate the impacts flooding for up to 1 in 200 year flood events that for properties alone were estimated to result in damages in excess of £400 million (as outlined in (Evans, 2019)).

With limited model runs within the central city region the reduction of infrastructure vulnerabilities were investigated in the scope of properties, traffic, and infrastructure within this area. For the traffic modelling side the analysis within this document has highlighted that crucial road sections that connect the South and the North of the city are susceptible to flooding and could have potential implications to traffic flows within the city. Analysis taken from this study will be utilized in an updated traffic model with the subsequent impact assessments discussed in the accompanying follow-on deliverables (D3.5 and D3.6). From the properties and energy sectors side the follow-on deliverables will investigate how localized changes/protection to infrastructures can mitigate impacts.

An additional outcome of the analysis within this document and in the RESCCUE project is that it has acted as a focus for developing a multi-agency strategy (between Bristol City Council, Wessex Water and the Environment Agency) for dealing in a holistic way with flooding arising from connected watercourses and drainage systems. These outcomes have been analyzed specifically within the Ashton catchment (as outlined in the section 3.3.3.). It is envisioned that this analysis would be transferable to other regions in the city and elsewhere, where data available.

4 Assessment of climate hazards reduction for Lisbon Research Site

4.1 Summary of multi-hazards and multi-risk assessment for Baseline and BAU scenarios

Summary and main characteristics of the research site

Lisbon city, Portugal's capital, covers an area of approximately 85 km^2, has a resident population of 547 733 inhabitants, but doubles with daily commuters. Located by Tagus River, has an extensive river front of almost 16 km and a temperate climate, classified as Mediterranean, characterized by dry and hot summers and wet and fresh winter periods (Vela, 2017) Relevant sectors in Lisbon include water supply, wastewater and stormwater, power supply, transports and waste collection. Water supply is outside the scope of Lisbon research site but climate change impacts have been extensively addressed by the managing utility EPAL.

Services related to the water cycle dealt with within RESCCUE, include Lisbon wastewater and stormwater systems, having both combined and separate sewers, with a total length around 1,400 km and a variety of dimensions, materials and age. Management of these systems is by the municipality (CML). Systems' outlets are at the Tagus estuary and estuary water level can influence performance, especially under the effects of tides, storm surges and average sea level rise. Wastewater treatment is carried out at three main plants, managed by the wastewater utility AdTA. The complex and largely combined sewer system, includes separate sewers, as well as dendritic and looped sewer networks. To face downstream conditions, such as tides and storm surges, controllers are installed including weirs and tidal valves. Dry weather flows are directed to the treatment systems, and weir levels allow discharge of excessive wet weather flows to Tagus River "relieving" the network and reduce flooding.

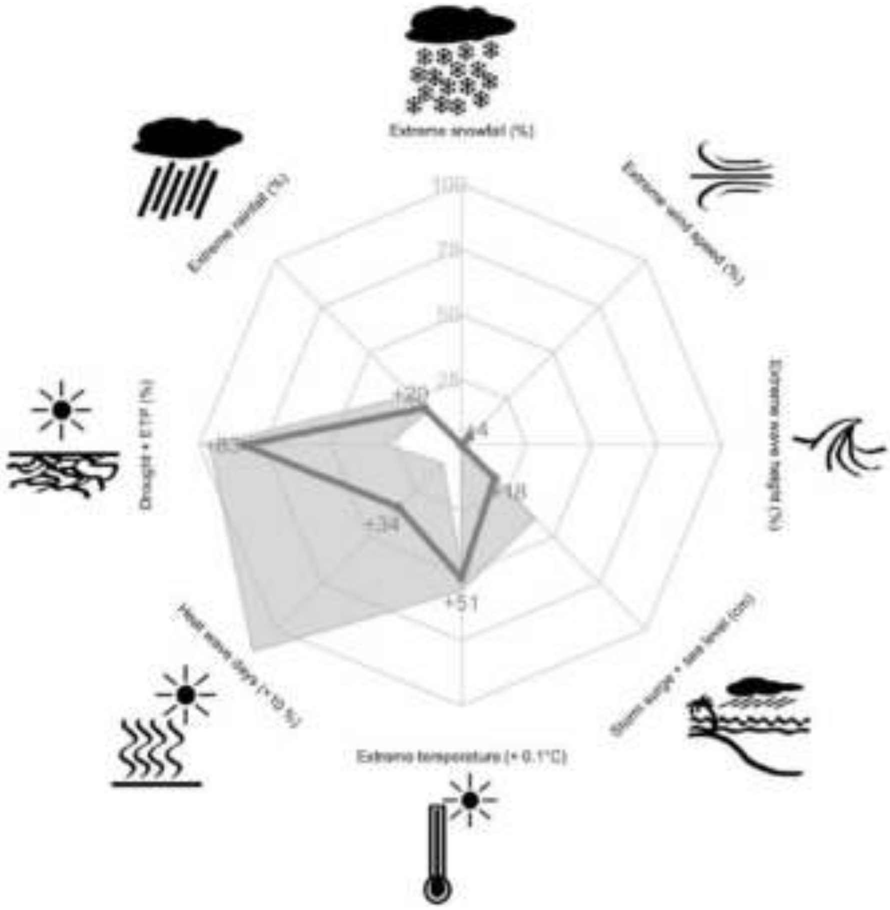
EDP Group is the largest energy producer, distributor and supplier of electricity in Portugal. In the distribution activity, the transported energy is channelled through the distribution grid. The distribution network conveys the flow of energy to the supply points. Electricity distribution networks 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.

Regarding mobility, study of the road transport system in Lisbon includes not only the roads network but also some structures, such as tunnels and viaducts, and passenger interfaces. A number of terminals and other interfaces provide connections between several types of transportation, both public and private. A number of organizations manages the existing rail network: Infrastructures of Portugal S.A., Lisbon's Transports, Lisbon's Metropolitan (ML), Carris and others.

Regarding wastes, the municipality (CML) handles the collection and the transport of undifferentiated and recyclable waste services in Lisbon.

General presentation of climate hazards

Paradinas *et al.* (Paradinas *et al.*, 2019) presented a summary of the results on climate change in Lisbon within RESCCUE project, as represented in Figure 97. The results show a probable progressive increase of the rainfall intensity in Lisbon over time for all return periods. Additionally, for the periods 2041-2070 and 2071-2100, the increase of the rainfall intensity appears to increase slightly with the return period.



Note: Extremes compass rose for Lisbon - maximum point change in climate extreme events along the century (return periods between 2 and 100 years). Centre represents no changes; edge corresponds to an increase of 100% for every variable except for heat wave days (border is +1000%) and extreme temperature (border is +10°C). Thick lines: median scenario; shaded area: uncertainty region (5-95%). Snowfall and wave height not considered for Lisbon.

Figure 97: Climate change results for Lisbon: extremes compass rose (Paradinas et al., 2019).

Since hazards selected for development of RESCCUE for Lisbon city are those related to flooding, the main variables of interest are the precipitation and estuary water level.

Definition of the current scenario of precipitation, used as baseline or current situation (CS), the IDF curves for the IGDL meteorological station of Brandão *et al.*, (Brandão, Rodrigues and Costa, 2001) are used. The rainfall intensities for climate change scenarios (CC) are estimated with the same basis and by using the change factors obtained in Deliverable 1.3 (Monjo *et al.*, 2018). Analysis of extreme precipitation peaks lasting less than 1 hour is important in Lisbon, since several catchments in critical areas have concentration times below 1 hour. The resulting aggravated IDF curves are the base for the definition of the rainfall events for the climate change scenarios. IDF curves for CS and CC scenarios are presented in Figure 98. Following the results of Paradinas *et al.* (Paradinas *et al.*, 2019), climate change scenarios (CC) were selected for the "business as usual" situation (BAU) and for adaptation alternatives. Rainfall events for simulations were carried out using a standard design hyetograph as given in Figure 99.

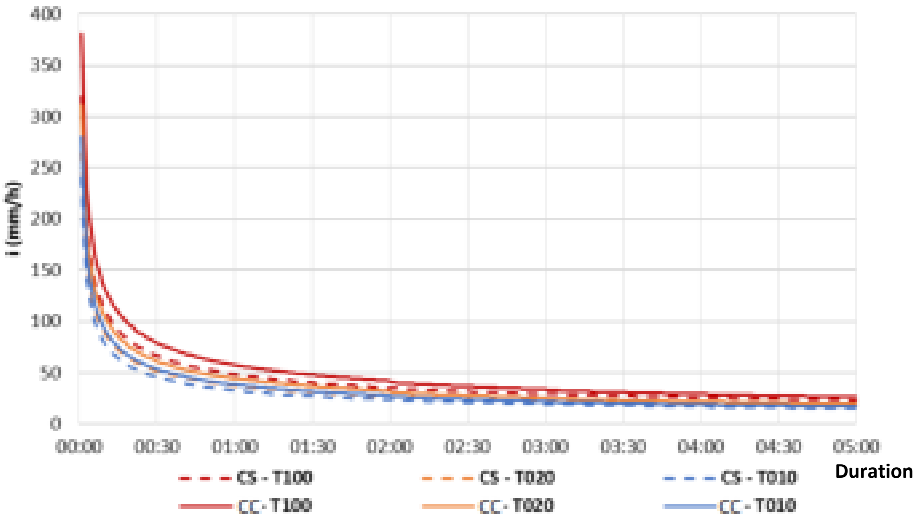


Figure 98: IDF Curves of Lisbon-IGIDL station: current situation (CS) and climate change (CC) scenarios

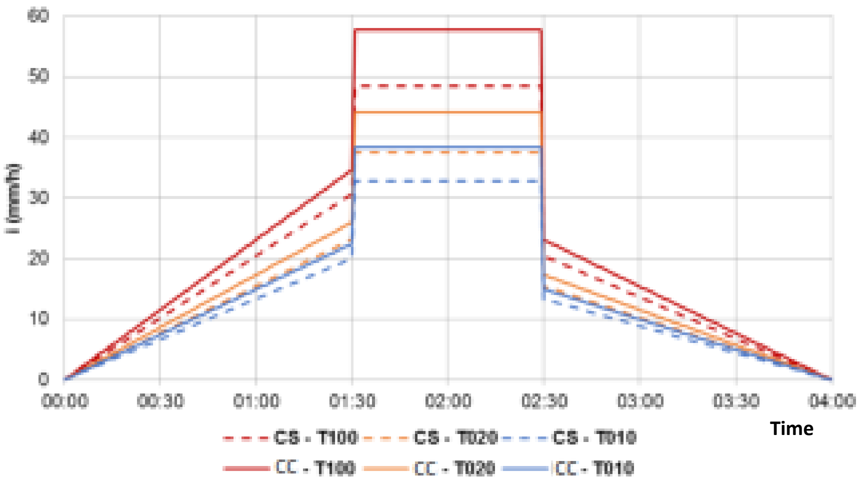


Figure 99: Design hyetographs adopted for hydraulic simulations for Lisbon.

For estuary water level (since it varies with tides during the day), a non-extreme situation was assumed for both CS and CC. As considered in Deliverable 2.2 (Russo, 2018a), the tide level of 6/7 of the projected value was assumed, resulting in a tide level of 1.95 m and 2.81 m for CS and CC, respectively.

These scenarios are used to proceed with simulations for both BAU (Russo, 2019, D2.3) and for the selected adaptation strategies and measures as detailed in the present report.

Sectorial / integrated models developed within the research site

Sectorial models available for use in RESCCUE include drainage systems and electrical supply but the former is still incipient and simplified (developed for planning purposes). For the mobility and wastes sectors, models to assess performance under climate change scenarios are not available for the city of Lisbon. A simplified approach is assumed to allow estimating impacts on these infrastructures and associated services. Additionally, modelling results for the scenarios of estuary water level are available from another study promoted by CML (Antunes, Rocha and Catita, 2017).

Therefore, for Lisbon the modelling efforts are concentrated in the urban drainage and estuary water level. The main characteristics are briefly described in section 4.3. Further details can be found in Deliverable 2.2 (Russo, 2018a).

The current situation (CS) simulations (presented in detail in Deliverable 2.2) were carried out for the scenarios presented in Table 29. In Deliverable 2.3 (Russo, 2019), to ensure the comparison with selected future climate scenarios, the 1D GIS Model was also run for T = 100 years (current situation), which was not previously included in Deliverable 2.2. In Table 30 the scenarios selected for climate change are presented, used in Deliverable 2.3 for the situation of BAU and are used in the present report for the adaptation strategies simulations.

Table 29: Simulation scenarios for Lisbon urban drainage models – Current situation.

Scenario Code	Rainfall Event Return Period	Tide Level	1D GIS Model	1D/2D CMSB
CS-T002	T = 2 years	1.95 m	✓	✓
CS-T010	T = 10 years		✓	✓
CS-T020	T = 20 years		✓	✓
CS-T050	T = 50 years		✓	✓
CS-T100	T = 100 years		✓	✓

Table 30: Selected climate change scenarios (CC) for Lisbon for BAU and adaptation alternatives simulations.

Scenario Code	Rainfall Event Return Period	Tide Level	1D GIS Based	1D/2D CMSB
CC-T010	T = 10 years	2.81 m	✓	✓
CC-T020	T = 20 years		✓	✓
CC-T100	T = 100 years		✓	✓

Main results for current situation and BAU scenarios

The results for current situation (CS as baseline) and climate change scenarios (BAU, business as usual) allowed estimating the impacts associated with effects of climate change locally and for the hazards assessed (flood related).

Citywide assessment 1D GIS Based

Using the simplified approach to evaluate the city as a whole, the aggravation in the use of sewer capacity as response to flows generated is clear, for the three return periods. The comparison in use of sewer capacity and corresponding variation as effect of climate change, i.e. BAU-CD using values presented in previous sections, for each return period, are presented in Figure 100 and Table 31. Considering climate change drivers and the hazard classification adopted, it is found that the urban drainage performance is mostly aggravated for T100 scenario, where there is a worsening of the hazard classification on 13.2% for the analysed sewers. For T010 and T020, this change is of 11.7% and 9.0%, respectively.

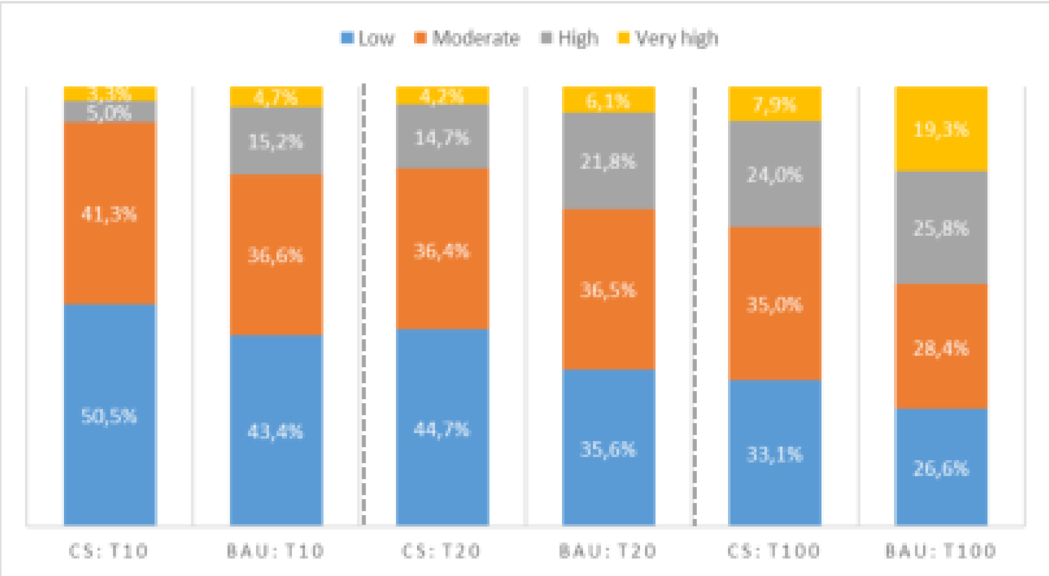


Figure 100: Use of sewer capacity: results for current and BAU situations.

Table 31. Citywide assessment of use of sewer capacity - comparison between CS and BAU.

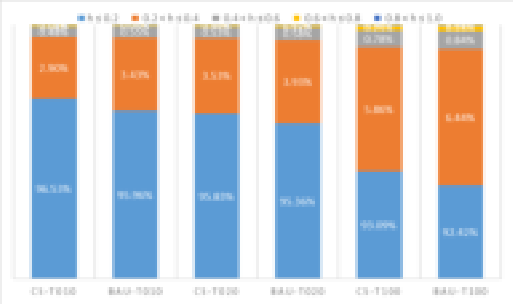
Use of sewer capacity	Return period (%(BAU-CS))		
	T010	T020	T100
Low	-7.1	-9.1	-6.6
Moderate	-4.6	+0.1	-6.6
High	+10.2	+7.1	+1.7
Very high	+1.5	+1.9	+11.4

Lisbon downtown catchments J and L

Assessment of flooding water level hazard. The results for the Lisbon downtown area detailed modelling (Figure 101a) allow to conclude that variations are small for flooding water level hazard from current situation to climate change scenarios simulated.

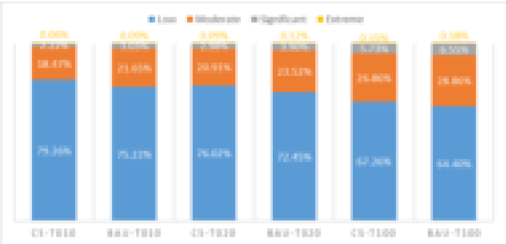
Assessment of hazard to pedestrians. For pedestrian hazard assessment results (Figure 101b), it is observed an overall aggravation of the pedestrian hazard classification around 4.0, 3.6 and 2.9 for the T010, T020 and T100 return periods, therefore showing a decrease with the return period. As for the other results, response is due not only to the increase of the rainfall precipitation but also to sea level rise.

Assessment of hazard to vehicles. Overall, results for the assessment of hazard to vehicles (Figure 101c), follows the same trend as the assessment of hazard to pedestrians.



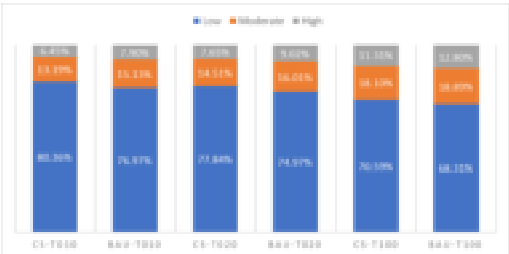
Flooding water level (m)	Hazard class	Return period (%(BAU-CS))		
		T010	T020	T100
d ≤ 0.2	Very low	-0.57	-0.47	-0.67
0.2 < d ≤ 0.4	Low	+0.53	+0.40	+0.58
0.4 < d ≤ 0.6	Moderate	+0.07	+0.05	+0.06
0.6 < d ≤ 0.8	High	-0.02	+0.02	+0.03
0.8 < d ≤ 1.0	Very high	-0.01	+0.00	+0.00

(a) Flooding water level hazard



Pedestrian Hazard level	Return period (%(BAU-CS))		
	T010	T020	T100
Low	-4.0	-3.6	-2.9
Moderate	+3.19	+2.61	+2.00
High	+0.82	+0.92	+0.82
Very high	+0.04	+0.03	+0.03

(b) Pedestrian hazard assessment



Hazard to vehicles level	Return period (%(BAU-CS))		
	T010	T020	T100
Low	-3.39	-2.88	-2.28
Moderate	+1.94	+1.50	+0.79
High	+1.45	+1.38	+1.49

(c) Hazard to vehicles

Figure 101: Flooding water level, pedestrian, vehicle hazards - CS and BAU situations summary.

As a general conclusion, especially for downtown catchment J and L, results do not provide evidence of significant effects from climate changes in hazards associated with flooding, to properties, pedestrians and vehicles. Consequently, the implications to the mobility, to waste and to electrical sectors were found to be low.

The impacts of flooding on the **electrical infrastructure** are similar for CS and BAU scenarios, once the critical components have effects at the same level. The electrical infrastructure in Lisbon was found to be quite resilient to flooding events.

For **mobility**, differences from CS to BAU scenarios are low, with variations above 5% in length just obtained for local situations for T100, for water level up to 0.4 m, and global values are relatively stable. For tide-induced flood, results show little variations for roads, with no exposure for railways.

For **wastes**, globally, variations are very low and values not considered significant. For the collection mode “door-to door”, the predominant mode in these catchments, variations are below 1%. For the remaining modes, representing low numbers in locations and bins, differences observed are up to 5%. For tide-induced flood, only elements in the “door to door” waste collection mode are exposed, up to 2% locations and around 1% bins.

4.2 Adaptation strategies and measures to cope with climate change for the city of Lisbon

Adaptation strategies selected for Lisbon

The city of Lisbon has been considering the future climate impacts and is actively committed with climate change adaptation, integrating initiatives and measures to reduce the risks of natural and human systems against the effects of climate change, whether effective or expected.

As described in Deliverable 5.2 (Martínez ‐ Gomariz, 2019), the measures considered to work with in RESCCUE project are aligned with the implementation of a number of municipal strategies including the Municipal Climate Change Strategy (CML, 2017), the Sustainable Energies and Climate Action Plan (CML, 2018) and the Metropolitan Plan for Climate Change Adaptation (AML, 2019). The adaptation strategies identified for Lisbon within RESCCUE project are listed in Table 32. The models in use for evaluation of the effect of the adoption of adaptation strategies and resulting hazard level are, as described, hydraulic models. Most strategies do not require the analysis by means of modelling and therefore three measures are selected for modelling as highlighted in the table.

Table 32: List of strategies for Lisbon

ID	Strategy
S001Lisbon	Improve knowledge: city characteristics and vulnerabilities to flooding
S002Lisbon	Redesign urban landscape to enhance the water cycle functions: nature based solutions
S003Lisbon	Redesign urban landscape to enhance the water cycle functions: structural solutions
S004Lisbon	Improve the resilience level at riverfront
S005Lisbon	**Adaptation of green infrastructure**
S006Lisbon	Increase ecosystem services: human well-being
S007Lisbon	Promote urban rehabilitation as a tool to increase resilience: sewer systems
S008Lisbon	Promote urban rehabilitation as a tool to increase resilience: facing climate change
S009Lisbon	Promote citizenship and create networks to involve key stakeholders
S010Lisbon	Strengthening collaboration within AML, Parishs and municipality departments
S015Lisbon	**Peak flow attenuation through the construction of two retention basins**
S016Lisbon	**Construction of new components in drainage system**
S011Lisbon	Improving drainage in the underground components of the electrical infrastructure
S012Lisbon	Engaging people in citizenship campaigns
S013Lisbon	Awareness about flooding risks
S014Lisbon	Update risk maps
S017Lisbon	Lisbon drainage monitoring and early-warning system
S018Lisbon	Architecture integration/solutions adaptations for urban electrical infrastructure to face overland flows or coastal water overtopping
S019Lisbon	Building protections for urban electrical infrastructure, exposed to estuarine flood
S020Lisbon	Use alternatives water sources taking into account severe droughts

Adaptation strategies and measures selected for simulation with available models

For the adaptation strategies selected for simulation using the available models, the measures considered most relevant by stakeholders to implementation of these strategies are listed in Table 33, as detailed in Deliverable 5.2 (Martínez - Gomariz, 2019).

Table 33: Strategies (S) compatible with modelling for Lisbon and corresponding measures (M).

ID	Strategy / measures
S005Lisbon	**Adaptation of green infrastructure**
M001FLOOD	Bioretention area;
M014FLOOD	Implementation of Rainwater Harvesting systems (RWH);
M003DROUGHT	Prioritize water allocation in a stress situation;
M002HEATWAVE	Build/promote urban forest and park.
S015Lisbon	**Peak flow attenuation through the construction of two retention basins**
M008FLOOD	Identify high risk areas by conducting studies involving flood modelling analysis;
M031FLOOD	Provide flood storage areas via detention, retention or infiltration basins;
M068FLOOD	Create multi- purpose areas on flood storage areas.
S016Lisbon	**Construction of new components in drainage system**
M016FLOOD	Rehabilitate sewer pipes;
M017FLOOD	Inlets increase;
M023FLOOD	Construction of diversion tunnels;
M027FLOOD	Construction of anti- pollution basins.

For the hydraulic modelling of these strategies, the measures that are compatible with model parametrization and application are as follows: for strategy S005Lisbon, the measures that are influencing the situation simulated are M001FLOOD and M002HEATWAVE, since are those that lead to the increasing of the permeable areas; for strategy S015, the measure that is simulated is M031FLOOD; for strategy S016, the measures included in the simulation are M0017FLOOD and M023FLOOD.

The identification of the simulations is structured as presented in Table 34.

Table 34: Identification of the simulations of climate change scenarios (CC) for Lisbon for each climate adaptation strategies (CAS).

ID	Strategy	CC scenario code	Rainfall Event Return Period	Tide Level
CAS1-010 CAS1-020 CAS1-100	S005	CC-T010 CC-T020 CC-T100	T = 10 years T = 20 years T = 100 years	2.81 m
CAS2-010 CAS2-020 CAS2-100	S015	CC-T010 CC-T020 CC-T100	T = 10 years T = 20 years T = 100 years	
CAS3-010 CAS3-020 CAS3-100	S016	CC-T010 CC-T020 CC-T100	T = 10 years T = 20 years T = 100 years	

4.3 Urban Drainage Sector

4.3.1 Introduction and summary of specific climate hazards and risk for the urban drainage sector

Lisbon drainage system has three main subsystems (Alcântara, Chelas and Beirolas) each served by a WWTP. The sewer network, with components at least from the beginning of the XVIII century, and has been subject to expansions and modifications numerous times.

Network mapping review and collection of information for performance assessment is under development by CML. However, these data will not be available under RESCCUE project timeline and the models herein applied use the available data. Historical data from flooding events is available and was used to map past occurrences' statistics (Details in Deliverable 2.2 (Russo, 2018a)).

Hydraulic models available are simplified, either in detail or in scope. Therefore, the urban drainage modelling for Lisbon research site has been carried out using two approaches, each with distinct geographical scopes, described in detail in Deliverable 2.2, as follows:

1. **Lisbon Municipality citywide drainage system – 1D GIS Model**: the main output is the hydraulic capacity of the main sewer system network. Due to its simplified modelling process, the 1D GIS Model is used to simulate the sewers' capacity facing estimated wet weather flows, for different return periods, testing the hydraulic behaviour of the system by applying the Manning-Strickler equation.
2. **Lisbon Downtown catchments J&L – 1D/2D Combined Model SWMM+BASEMENT (CMSB)**: main outputs include flooded areas, surface water levels and hydraulics in sewer network. This model allows integrating the performance results of the drainage system facing different return periods and tide levels into the surface runoff modelling.

Hazards selected for Lisbon research site are those related to flooding, as mentioned previously. Depending on the available information and model used, different criteria are applicable, resulting in a more comprehensive understanding of the hazards. In Table 35, a summary of definition of flooding related hazards for different approaches and scenarios is given as used in Deliverables 2.2 (Russo, 2018a), 2.3 (Russo, 2019) and 3.4 (Evans, 2019). For current situation, the historical data on flooding events allowed obtaining hazard maps with areas as a function of flooding frequency, used to cross-validate the results from the simulations.

Table 35: Definition of flooding related hazards for different approaches and scenarios.

Data/model	Criteria: metric, scale classes	Scenarios
Citywide historical records of flooding	**Flooded areas**: frequency, medium, high, very high hazard	CS
Citywide 1D GIS Based	**Use of sewer transport capacity**: $C = Q_{wet}/Q_{full}$ (%), 4 classes, low C ≤ 0.5, moderate 0.5 < C ≤ 1.0, high 1.0 < C ≤ 1.5, very high C > 1.5	CS, CC
Downtown catchments J&L 1D/2D CMSB	**Flooding water level**: water depth at critical time (m), 5 classes, very low d ≤ 0.2, low 0.2 < d ≤ 0.4, moderate 0.4 < d ≤ 0.6, high 0.6 < d ≤ 0.8, very high 0.8 < d ≤ 1.0 **Flooding hazard to pedestrians**: Flood hazard rating $HR=d \times(v+0.5)+DF$ (d - water depth (m), *v* - overland flow velocity (m/s), DF - debris factor (Defra and EA, 2005), 4 classes, low C ≤ 0.75, moderate 0.75 < C ≤ 1.25, high 1.25 < C ≤ 2, very high C > 2 **Hazard to vehicles**: *F(flow depth D, flow velocity* $\|\vec{v}\|$*)* (Martinez et al, 2017), 3 classes, low D ≤ 0.28 and $D \times \|\vec{v}\| \leq$ 0.40, moderate D ≤ 0.28 and 0.40 < $D \times \|\vec{v}\|$ ≤ 0.55, high D > 0.28 or $D \times \|\vec{v}\|$ > 0.55	CS, CC
Estuary water level	**Area as a function of simulated water level** modelling results for the scenarios of estuary water level are available from another study promoted by CML (Antunes et al., 2017).	CS, CC

The comparison for the existing system between the results for current situation (CS as baseline) and climate change scenarios (BAU, business as usual) allows estimating the impacts associated with effects of climate change locally and for the hazards assessed.

Citywide assessment 1D GIS Based

Using a simplified approach to evaluate the city as a whole, the aggravation due to climate change scenarios in the use of sewer capacity as response to flows generated, the variation as simulated as the effect of climate change (%(BAU-CD)), are presented in Table 36. Facing the considered climate change drivers and the hazard classification adopted, the urban drainage performance is mostly aggravated for T100 scenario, where there is a worsening of the hazard classification on 13.2% of the analysed sewers. For T010 and T020, this change is of 11.7% and 9.0%, respectively.

Table 36: Citywide assessment of use of sewer capacity - comparison between CS and BAU.

Use of sewer capacity	Return period (%(BAU-CS))		
	T010	T020	T100
Low	-7.1	-9.1	-6.6
Moderate	-4.6	+0.1	-6.6
High	+10.2	+7.1	+1.7
Very high	+1.5	+1.9	+11.4

The results obtained from the cross-validation for the CS scenario shows limitations of this simplified model, which have to be taken into account in the assessment (Figure 102).

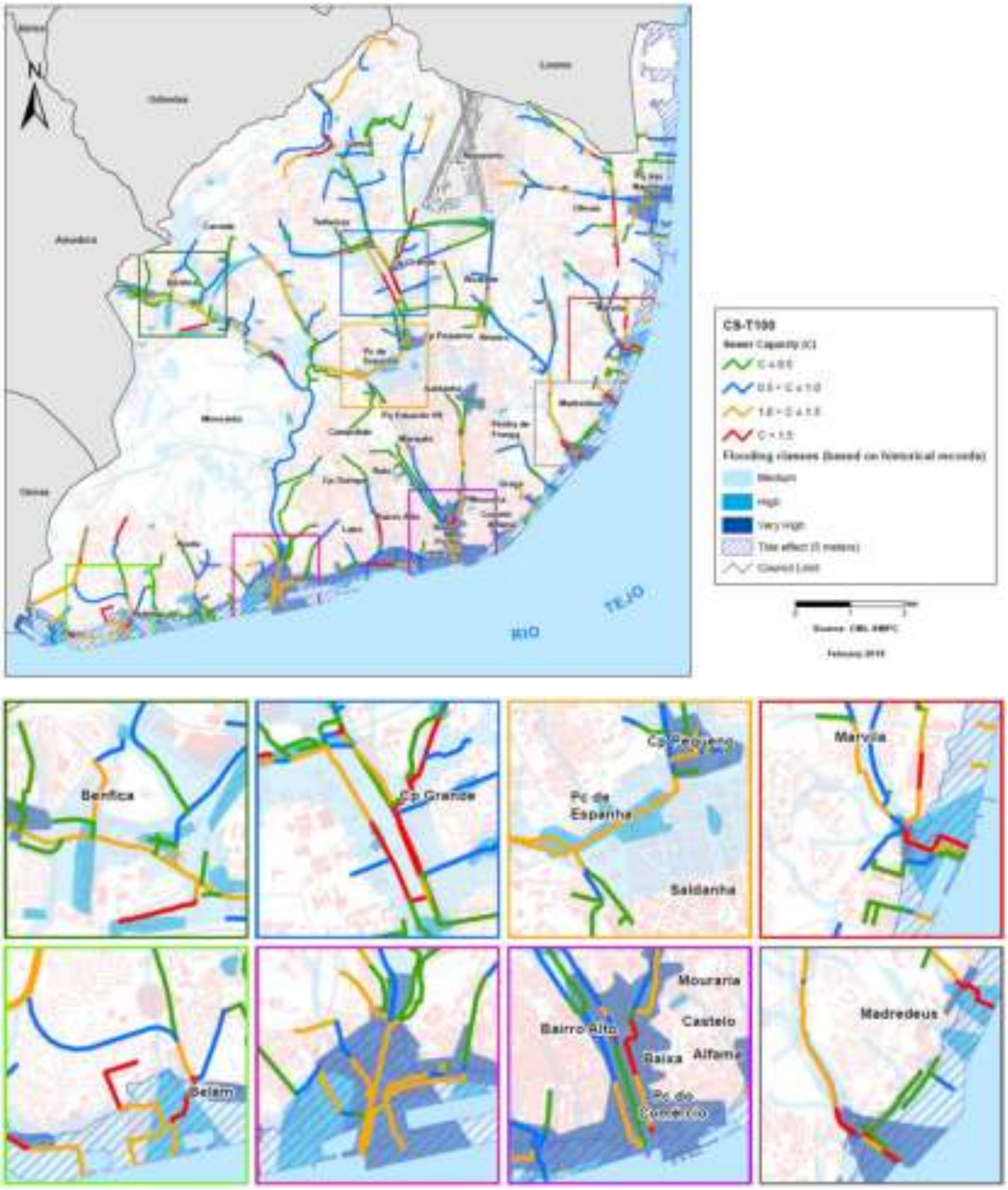


Figure 102: Use of sewer capacity at primary sewers (CS-T100) and flooding hazard based on historic observations.

Downtown catchments J+L 1D/2D CMSB assessment

Assessment of flooding water level hazard

Results of the detailed (CMSB) simulation of Lisbon downtown catchments J and L include flooded areas, surface water depths and flow velocity, allowing the analysis of the impact of overland flows on people, urban infrastructures or assets (D3.4). As expected the areas flooded and associated water depth (d) are increasing with the rainfall return period.

The comparison of results between baseline (CS) and BAU, for flooding water level hazard, are in Table 37. The results allow concluding that variations are small for flooding water level hazard from current situation to climate change scenarios. The noticeable variations are not so much with climate change but with increasing return period.

Table 37: CMSB results: Flooding water level hazard assessment - comparison between CS and BAU.

Flooding water level (m)	Hazard class	Return period (%(BAU-CS))		
		T010	T020	T100
d ≤ 0.2	Very low	-0.57	-0.47	-0.67
0.2 < d ≤ 0.4	Low	+0.53	+0.40	+0.58
0.4 < d ≤ 0.6	Moderate	+0.07	+0.05	+0.06
0.6 < d ≤ 0.8	High	-0.02	+0.02	+0.03
0.8 < d ≤ 1.0	Very high	-0.01	+0.00	+0.00

Assessment of flooding hazard to pedestrians

Flooding hazard to pedestrians has been analysed according to the methodology proposed and results are in Table 38. An overall aggravation of the pedestrian hazard of around 4.0%, 3.6% and 2.9%, respectively, for the T010, T020 and T100 return periods, is obtained, therefore showing a decrease with the return period. For instance, results for BAU-T010 are more severe than those obtained for the CS-T020. As for the other results, response is due not only to the increase of the rainfall precipitation but also to sea level rise.

Table 38: CMSB results: Pedestrian hazard assessment - comparison between CS and BAU.

Pedestrian Hazard level	Return period (%(BAU-CS))		
	T010	T020	T100
Low	-4.0	-3.6	-2.9
Moderate	+3.19	+2.61	+2.00
High	+0.82	+0.92	+0.82
Very high	+0.04	+0.03	+0.03

Assessment of hazard to vehicles

Although not considered in Deliverable 2.2 (Russo, 2018a) for Lisbon research site, the assessment of hazard to vehicles was estimated with the methodology proposed by Martínez *et al*. (Martínez-Gomariz *et al.*, 2017), using the Seat Ibiza.

The aggregated results for the assessment of flooding related hazard to vehicles, expressed as percentage of exposed area, are significantly overestimated for all simulations and classes of hazard since several large areas are not accessible to vehicles e.g. parks, sidewalks, among others. However, it is useful for comparison between scenarios. Results for the assessment of hazard to vehicles are in Table 39. Overall, the results regarding hazard to vehicles follows the same trend as the assessment of hazard to pedestrians. As a general conclusion, results do not provide evidence of significant effects from climate changes in hazards associated with flooding, to properties, pedestrians and vehicles.

Table 39: CMSB results: Assessment of hazard to vehicles - comparison between CS and BAU.

Hazard to vehicles level	Return period (%(BAU-CS))		
	T010	T020	T100
Low	-3.39	-2.88	-2.28
Moderate	+1.94	+1.50	+0.79
High	+1.45	+1.38	+1.49

4.3.2 Adaptation strategies, measures and design criteria

Modelling strategy S005 – Adaptation of green infrastructure (CAS1)

The modelling of the Strategy S005 was carried out for the whole city using the 1D GIS Model. The increase of pervious areas in the city is according to the relevant municipal strategies. Figure 103 illustrates the relative change (% increase) of green areas, modelled as pervious areas, in each drainage sub-catchment.

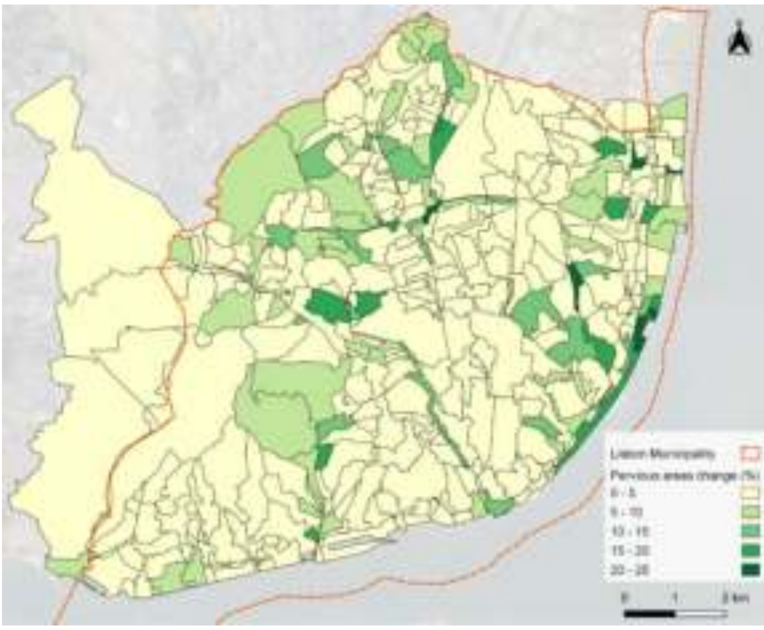


Figure 103. Green areas relative change (% increase from BAU to S005 implementation).

The detailed modelling of the downtown catchments J and L was not carried since the level of change is low.

Modelling strategy S015 – Peak flow attenuation by construction of retention basins (CAS2)

The strategy S015 model setup is based on the recommended interventions included in the Lisbon Drainage Plan 2016-2030 (HIDRA, ENGIDRO, BLUEFOCUS, 2015), namely the construction of two retention basins, one in Alto da Ajuda (catchment D) and the other in Ameixoeira (catchment S), as presented in Figure 104.

While the main objective of Alto da Ajuda retention basin is the reduction of the peak flows to the downstream pluvial network, the retention basin of Ameixoeira focus on solving problems related to significant debris dragging on the watercourse of Ameixoeira, characterised by a torrential regime, with high rain induced flows but dry during the remaining time.

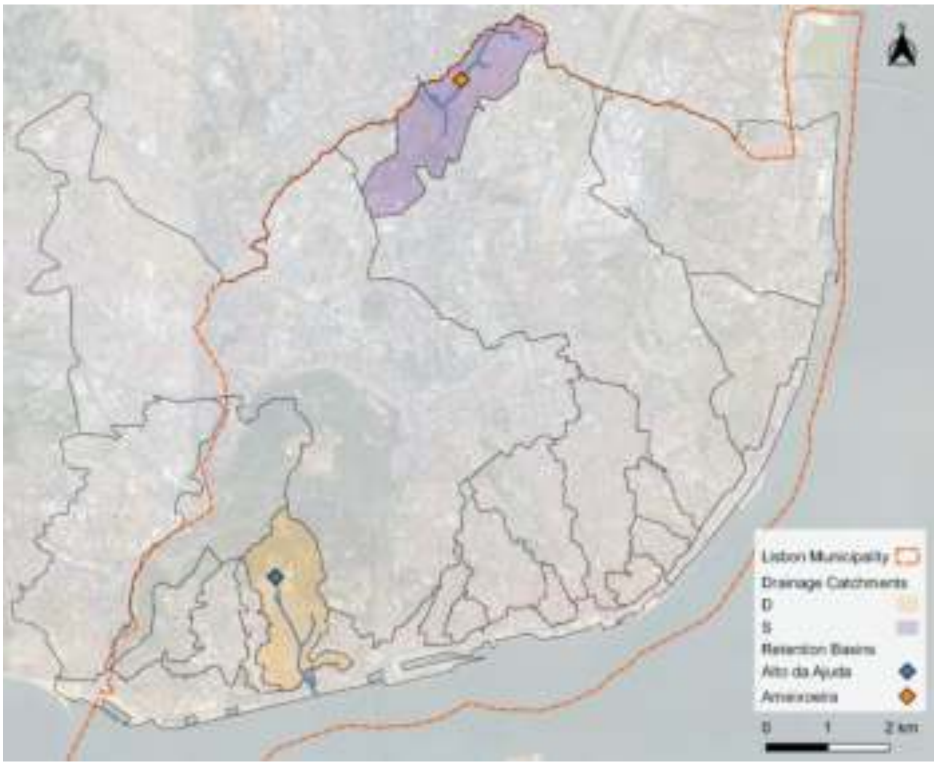


Figure 104. Location of the retention basins included in the CAS2 model.

The **retention basin of Alto da Ajuda** is located in the upstream part of catchment D, an area with reduced urban occupation, receiving contributions from an area of about 32 ha, representing 15% of the total area of the catchment. Studies carried during the design process resulted in the rainfall peak flows presented in Table 40.

Table 40. Rainfall peak flows for the catchment upstream of retention basin of Alto da Ajuda (HIDRA, 2017).

Return Period (years)	2	5	10	20	50	100
Peak flow (m^3/s)	1.18	1.58	1.84	2.07	2.37	2.60

A wall (weir) with a bottom orifice controls the flow downstream of the basin allowing an average discharge of 0.37 m^3/s. The design of the wall crest level assumes the discharge for a 100-year return period rainfall. The retention basin allows a reduction on the pluvial peak flows of about 80%, 82% and 86% for a 2, 10 and 100-year return period rainfall, respectively. The layout of the basin is presented in Figure 105 and, in Figure 106, some pictures of the construction works, finished in 2019, are shown.

Figure 105. Layout the retention basin of Alto da Ajuda and detail of the discharge chamber.

Figure 106. Retention basin of Alto da Ajuda during construction.

The **retention basin of Ameixoeira** is located in the catchment S and the upstream catchment has about 89 ha, with a significant percentage of impervious area. The studies carried during the design process resulted in the rainfall peak flows presented in Table 41.

Table 41. Rainfall peak flows for the catchment upstream of retention basin of Ameixoeira (AMBITEC, 2016).

Return Period (years)	2	5	10	20	50	100
Peak flow (m^3/s)	9.28	12.30	14.33	16.32	22.59	25.93

The retention basin of Ameixoeira is a small dam of about 5.30 m height with a storage capacity of about 2200 m^3, designed for the 100-year return period rainfall. This infrastructure has a permanent bottom discharge, a top discharge (*Cipoletti type*) and, for a 100-year return period rainfall, the overtopping discharge is for a maximum water height of 0.35 m above the crest. The design flow is about 26 m^3/s, with a bottom discharge of 9.7 m^3/s, a top discharge of 7.1 m^3/s and an overtopping discharge of 9.3 m^3/s. The design scheme is presented in Figure 107.

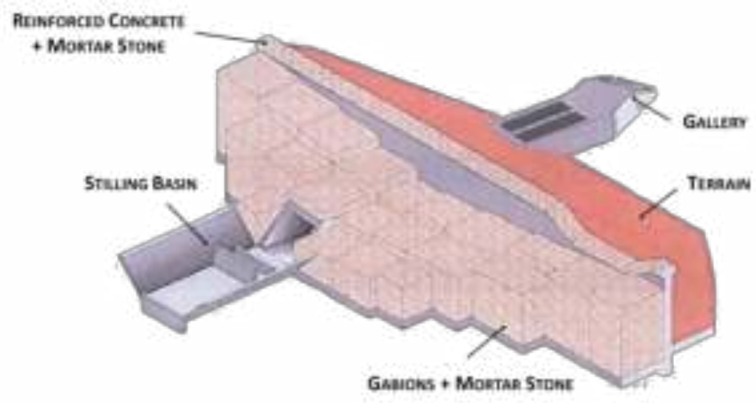


Figure 107. Design scheme of the retention basin of Ameixoeira (AMBITEC, 2016).

As previously mentioned, the effect on peak flow attenuation is expected to be minimal. In the model, an attenuation of 5% of the pluvial peak flows was assumed.

Modelling strategy S016 – Construction of new components in drainage system (CAS3)

The model setup for strategy S016 is also based on the recommended interventions included in the Lisbon Drainage Plan 2016-2030 (HIDRA-ENGIDRO- and BLUEFOCUS, 2015), namely for the measures of inlets increase and construction of diversion sewers.

For this strategy, two model approaches were used: Citywide 1D GIS Based and Downtown catchments J&L 1D/2D CMSB.

The main measure for this strategy lies on the construction in tunnel of two diversion sewers, named after its starting and ending locations, the Tunnel Monsanto – Stª Apolónia (TMSA) and the Tunnel Chelas – Beato (TCB). These sewers aim at diverting the flows from the upper catchments in order to alleviate the excess water reaching the downstream sewers allowing the use of the existing transport capacity to decreasing the flooding at the flat downstream areas of the city. Both tunnels are multi-purpose, providing both room for the sewers transporting pluvial induced flows and pipe to transport treated wastewater to reuse in compatible uses. The works intersect several major catchments (areas of intersected catchments in the city indicated in Table 42 and illustrated in Figure 108.

Table 42. Areas of the catchments intersected by the diversion tunnels (HIDRA, 2017).

Catchment (Intersection location)	Area (ha)
E (TM1)	2508
J (TM2)	87
J (TM3)	70
L (TM4)	220
O (TC)	1654

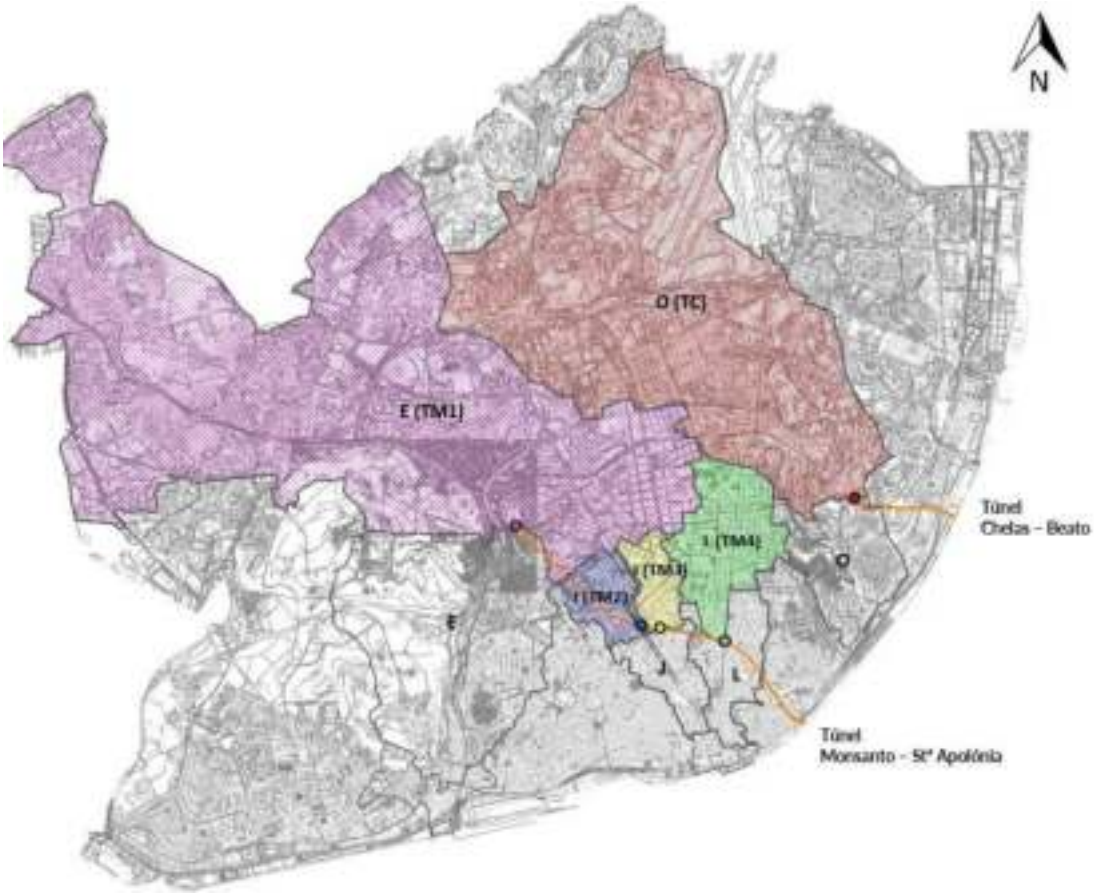


Figure 108. Tunnels: associated drainage catchments and intersection locations (HIDRA, 2018).

Tunnel Monsanto – Stª Apolónia (TMSA)

At the entry of the TMSA, the project includes a pollution retention basin designed with the aim of pre-treating the combined flows entering the sewer, since the water will be discharged into the Tagus River. After a rainfall event, the stored volumes and the retained solids are pumped to the Caneiro de Alcântara in order to be treated in the Alcântara WWTP. This pollution retention basin has a storage capacity of 16 000 m^3 and a treatment capacity of 7.5 m^3/s. For flows exceeding the treatment capacity, up to 43.5 m^3/s, are pre-treated by sieving.

The TMSA sewer is designed to transport 170 m^3/s (100-year return period rainfall), has a length of 4.6 km. With a circular cross-section with a diameter of 5.5 m, the sewer has slopes ranging between 0.45% and 0.83% at the initial and final lengths, respectively. The final length of the sewer can be under pressure flow, for the 100-year return period flow, with velocities between 7 and 8 m/s. The discharge cross section is rectangular, progressively widening, to reduce the discharge velocities down to about 2 m/s.

Apart from the initial length, at Quinta José Pinto, the TMSA sewer will intercept the existing drainage network at four intercepting manholes, two in Av. da Liberdade, one in Rua de Stª Marta and one in Av. Almirante Reis. Given the high depths of the tunnel, these manholes will be equipped, immediately downstream of the intercepted sewers, with a vortex drop shaft, to avoid deterioration by the intersected flows dropping from heights between 12.8m and 23.6m).

Tunnel Chelas – Beato (TCB)

The TCB design process also includes a pollution retention basin at the entry of the sewer, but it is not planned for the initial construction phase. Instead, a pre-treatment consisting of a sieving system with 36 m^3/s capacity will be initially installed. Since the intercepted sewers are combined, three diversion weirs are used to divert up to 3 times the dry weather peak flow to a sewer transporting the concentrated flows to the Chelas WWTP, upstream from the TCB sewer initial section. The TCB sewer is designed to transport of 147 m^3/s (100-year return period rainfall). The TCB is design for free-surface flow, with a minimum slope of 0.45%. Table 43 summarises the total intercepted design flows considered for TMSA and TCB sewers.

Table 43. Total intersected pluvial flows by the TMSA and TCB (HIDRA, 2017).

Return Period (years)	Total intersected flow (m^3/s)	
	TMSA	TCB
1	74.5	71.8
2	85.1	81.4
5	118.1	111.5
10	132.9	123.4
20	144.2	129.8
50	158.8	139.0
100	169.9	145.2

The improvement in capturing overland flows is also modelled mainly by the improvement of the efficiency of inlet devices both upstream from the diversion tunnels, to maximize its transport capacity and downstream in areas where topographic conditions are favourable to the water accumulation at the surface or to high flow velocities.

4.3.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

Modelling results for S005 – Adaptation of green infrastructure (CAS1)

Following the adopted methodology explained in Deliverables 2.2 and 2.3 (Russo, 2018a) (Russo, 2019), for the citywide **1D GIS Based** the results are based on the indicator of the sewer capacity to deal with the peak wet weather flow ($C = Q_{wet}/Q_{full}$) as described in section 4.3.1 The comparison between the BAU and CAS1 is presented in Table 44 and in Figure 109.

Table 44. Assessment of use of sewer capacity – comparison between BAU and CAS1 (CAS-BAU) (%).

Use of sewer capacity	Return period		
	T010	T020	T100
Low	+1.4%	+1.7%	+0.9%
Moderate	-0.6%	+0.0%	+1.4%
Significant	-0.0%	-1.0%	-0.9%
High	-0.8%	-0.7%	-1.5%

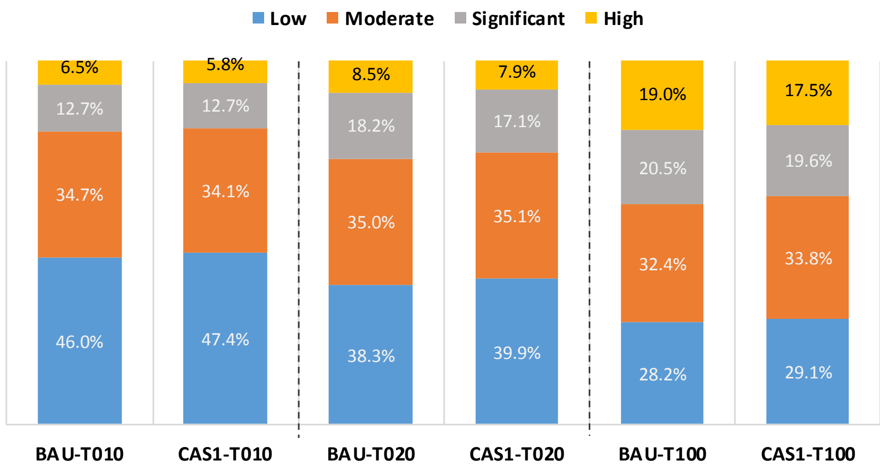


Figure 109. Use of sewer capacity: results for BAU and CAS1 situations.

Figure 110. Use of sewer capacity comparison with CS (%): BAU and CAS1.

The results reveal a slight increase in the overall drainage performance in the modelled sewer network. Nevertheless, as expected, this increase is not *per se* sufficient to increase the overall drainage performance significantly, or compensate the climate scenarios effect.

Due to the high occupation of constructed areas in Lisbon, there are few opportunities to increase considerably the effective pervious area in order to decrease the generated runoff. However, it is important to highlight that this strategy can produce, in some specific locations, good outcomes regarding the reduction of the peak wet weather flows. Additionally, the considered green infrastructures have multi-purposes and beneficial effects, such as temperature regulation and social welfare, which should be considered when assessing implementation benefits.

Modelling results for S015 – Peak flow attenuation by construction of retention basins (CAS2)

Figure 111 and Figure 113 illustrate the results for the citywide model terms of the sewer capacity use for the for the retention basins of Alto da Ajuda and Ameixoeira, for the corresponding catchments.

Looking at the impact in each catchment, for use of sewer capacity variation, only for Alto da Ajuda some beneficial effect was observed in the simulations results when comparing between the BAU and S015 situations (Figure 112 and Table 45). For Ameixoeira no impact was found, as expected from the project design specifications, and the impact on the drainage network performance regarding the use if the sewers' capacity is negligible. In fact, as mentioned before, this infrastructure aims at regularizing the watercourse of Ameixoeira instead of retaining the generated runoff.

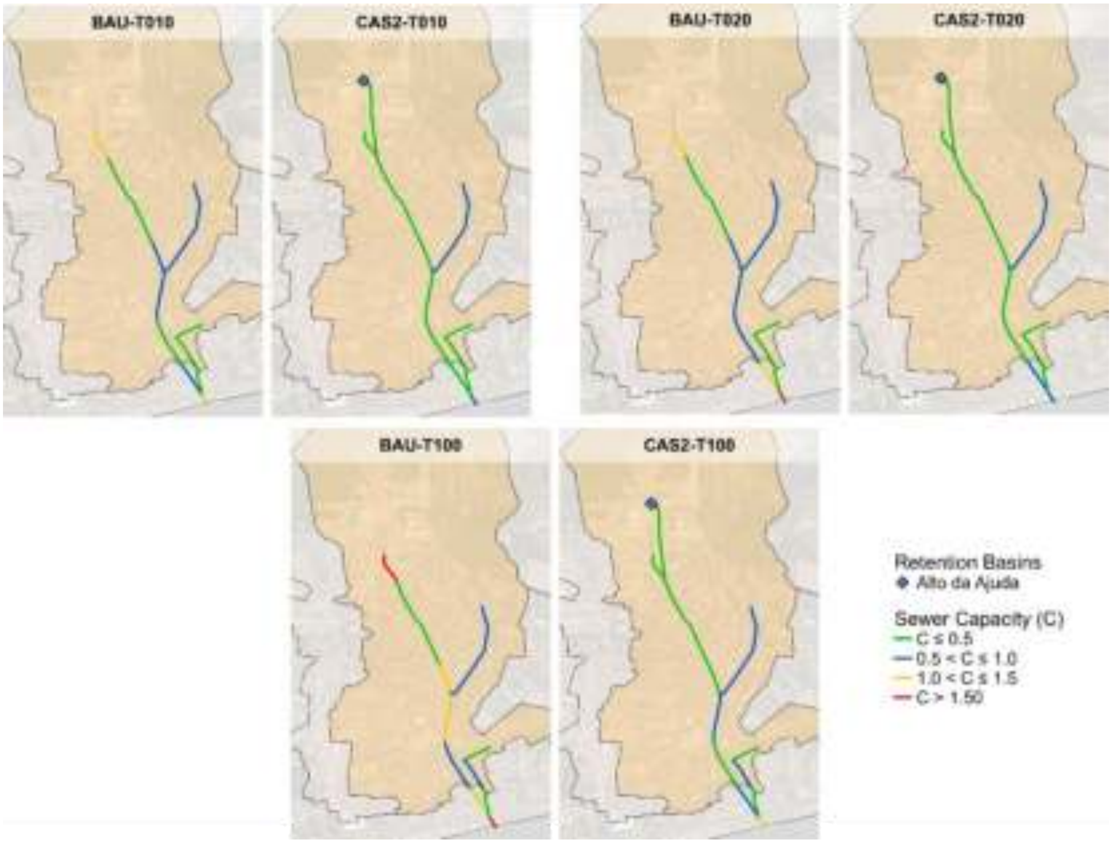


Figure 111. Use of sewer capacity: BAU and CAS2 (Alto da Ajuda).

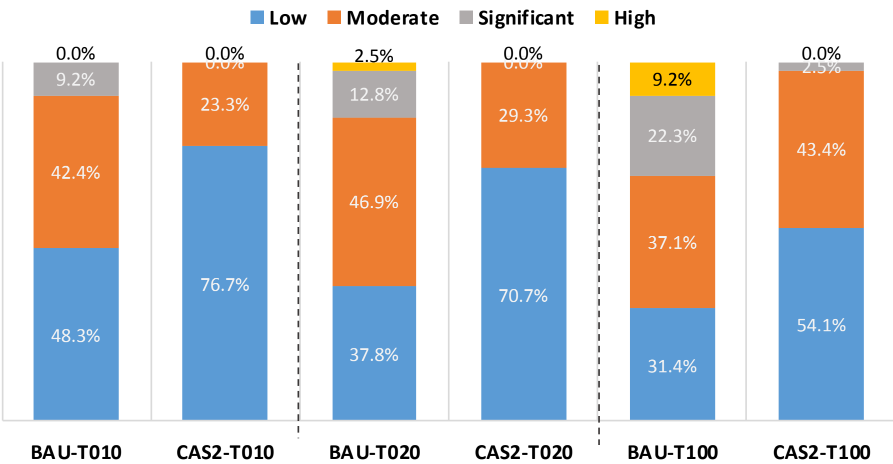


Figure 112. Use of sewer capacity: results for BAU and CAS2 (Alto da Ajuda).

Table 45. Use of sewer capacity – comparison between BAU and CAS2 (CAS2-BAU) (Alto da Ajuda).

Use of sewer capacity*	Return period		
	T010	T020	T100
Low	+28.4%	+32.9%	+22.7%
Moderate	-19.1%	-17.6%	+6.3%
Significant	-9.2%	-12.8%	-19.8%
High	0.0%	-2.5%	-9.2%

*Comparison considering only the sewer lengths existing in the BAU situation

From the results, the construction of the retention basin of Alto da Ajuda has a strong potential regarding the improvement of the drainage network performance. Due to the project design specifications, which lead to strong reductions of the pluvial peak flows, the percentage, in length, of the drainage network sewers, which use of capacity is classified as low or moderate is improved to about 100% for the 10-year and 20-year return period rainfall and about 97.5% for the 100-year return period rainfall.

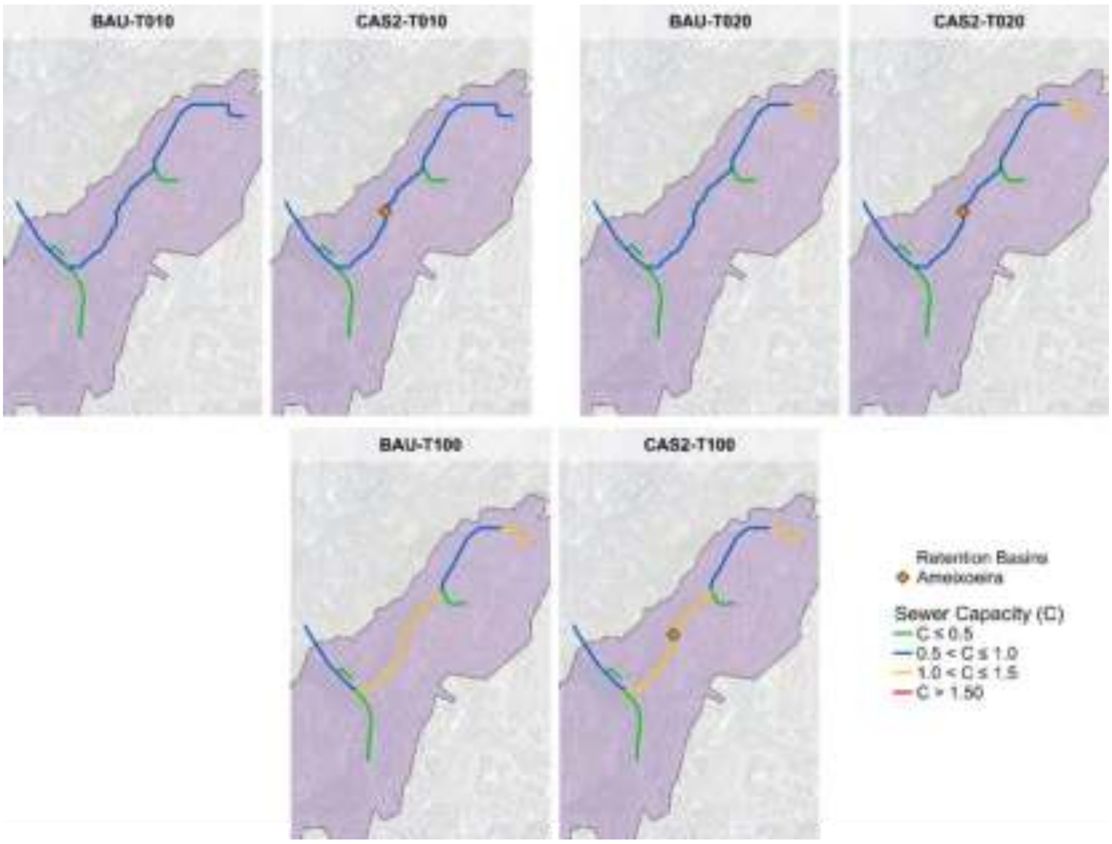


Figure 113. Use of sewer capacity: BAU and CAS2 (Ameixoeira).

The overall results regarding the use of sewer capacity for the whole city for CAS2 are presented in Table 46, comparing with BAU. Previous results are not significant at city scale even if minor benefit is obtained.

Table 46. Use of sewer capacity: comparison between BAU and CAS2 considering the whole city.

Use of sewer capacity	Return period		
	T010	T020	T100
Low	+1.1%	+1.3%	+1.7%
Moderate	-0.8%	-0.6%	-0.9%
Significant	-0.6%	-0.9%	-0.5%
High	+0.3%	+0.2%	-0.4%

Modelling results for S016 – Construction of new components in drainage system (CAS3)

The simulation of strategy S016 includes two out of the four measures considered. These two measures are materialized in the construction of two diversion tunnels, which improve the downstream sewers transport capacity and improvement of some inlets (only for the downstream catchments J&L). The combination of these measures was simulated with both models, the 1D GIS Model and the 1D/2D Combined Model, and results presented below.

Citywide 1D GIS model

The location of the catchments and sewers impacted by this strategy are presented in Figure 114. The results for the use of sewer capacity metric are mapped in Figure 115, Figure 116 and Figure 117, respectively, for 10, 20 and 100-year return period rainfalls. In these figures, the sewers located at downstream from the diversion tunnels are highlighted, since for the upstream sewers there are no changes in the drainage system performance.

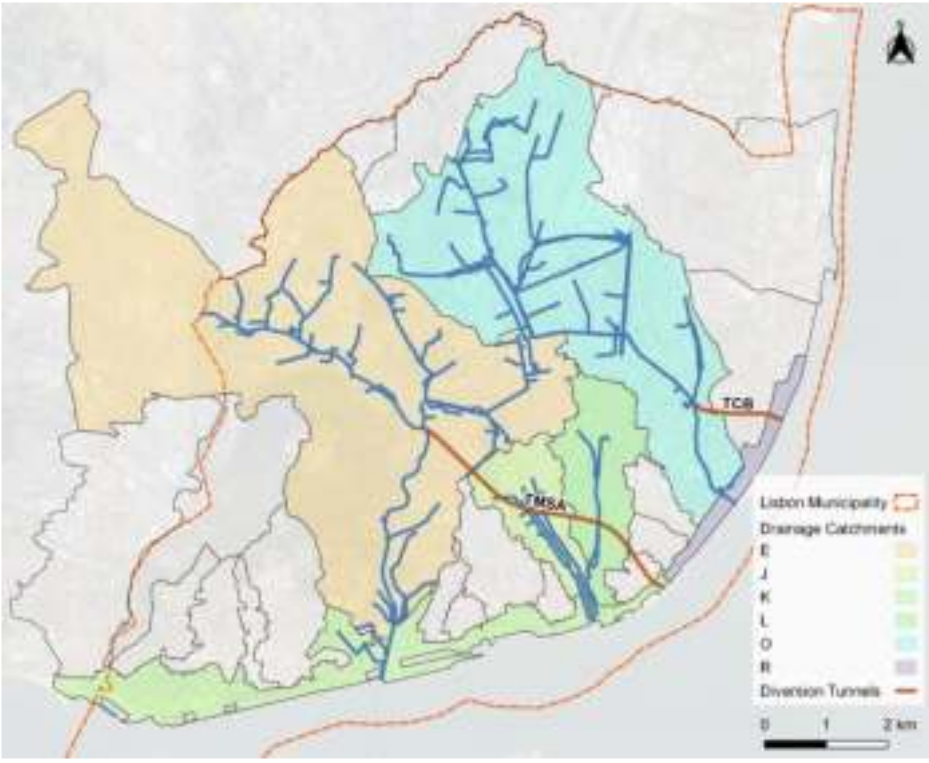


Figure 114. Diversion tunnels location, catchments involved and respective simulated sewers.

Figure 115. Use of sewer capacity classes map for CAS3-T010.

Figure 116. Use of sewer capacity classes map for CAS3-T020.

Figure 117. Use of sewer capacity classes map for CAS3-T100.

The comparison of results for the use of sewer capacity for the BAU and CAS3 situations are presented in Figure 118 and Table 47. Only the sewers downstream from the diversion tunnels are considered, excluding the tunnels' sewers, not including the upstream sewers where performance has no effect.

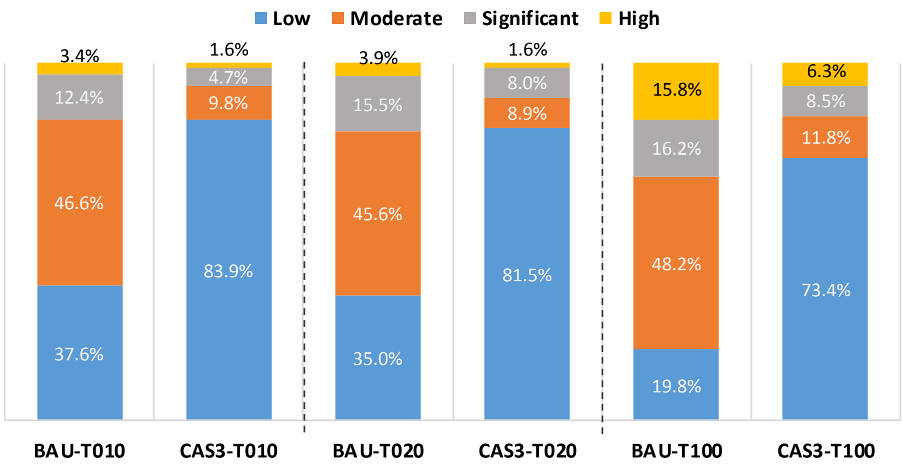


Figure 118. Use of sewer capacity: comparison of results for BAU and CAS3 (CAS3-BAU) (catchments downstream of intervention).

Table 47. Use of sewer capacity: comparison of BAU and CAS3 (CAS3-BAU) (catchments downstream of intervention).

Use of sewer capacity	Return period		
	T010	T020	T100
Low	+46.3%	+46.5%	+53.6%
Moderate	-36.9%	-36.7%	-36.4%
Significant	-7.7%	-7.5%	-7.7%
High	-1.8%	-2.3%	-9.5%

The results from simulations including the diversion tunnels shows a large improvement in the use of downstream drainage system capacity in the catchments downstream of the intervention. For all the return periods, a significant increase on the percentage of sewers in which available capacity is not exceeded (use of capacity classes low and moderate). Comparison with current situation (CS), allows concluding that simulation results of CAS3 also have the potential to improve with the existing climate situation (Figure 119).

Figure 119. Use of sewer capacity comparison with CS (%): BAU and CAS3 for catchments downstream of intervention.

Assessment of the effect for the whole city of this strategy resulted is not that significant (Figure 120), even if local effect is relevant.

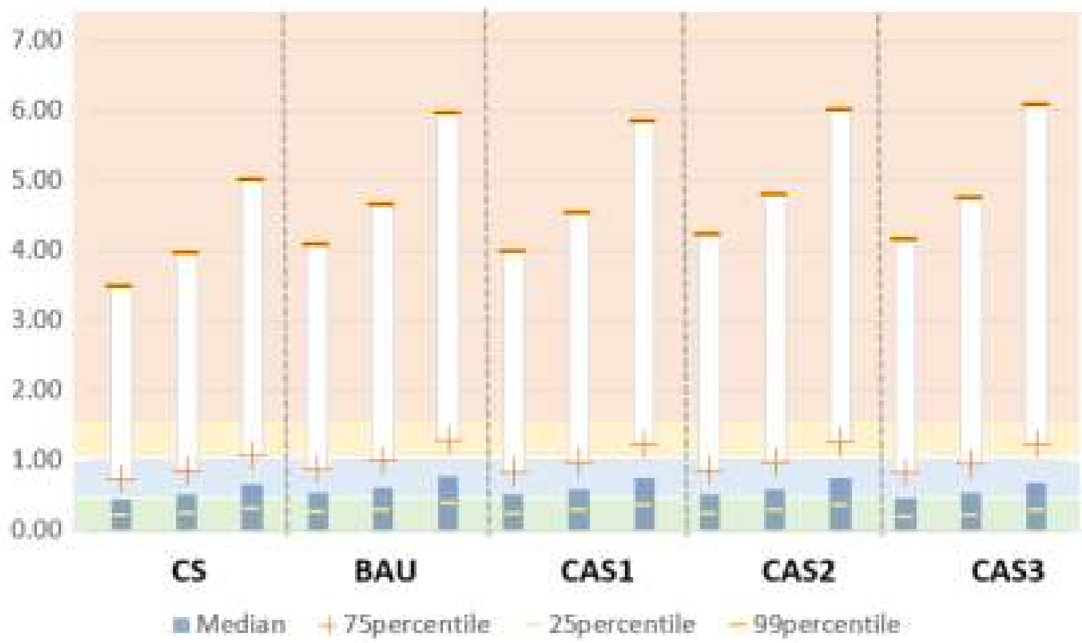


Figure 120. Statistics for use of sewer capacity (C) for situations modelled: results for the whole city (Bars left to right: T010, T020, T100).

Downtown catchments 1D/2D CMSB model

Benefiting from the development of the 1D/2D Combined Model SWMM+BASEMENT (CMSB) for the J and L catchments, the CAS3 situation was simulated considering not only the construction of the tunnels but also other measures that comprehend this strategy, namely the increase of runoff interception capacity with inlet devices and the correction of sewers, although in few locations.

Assessment of flooding water depth hazard. Following the same methodology as used in Deliverables 2.2 and 2.3 (Russo, 2018a) (Russo, 2019) to assess the flooding hazard related to the water depth, the results for CAS3 are in Figure 121, Figure 122 and Figure 123. These results are for surface water depths at a critical time step, i.e. worse situation of each simulation, approximately 2 hours and 40 minutes after the beginning of the rainfall event. This critical time step is similar to the one used for the CS and BAU situations.

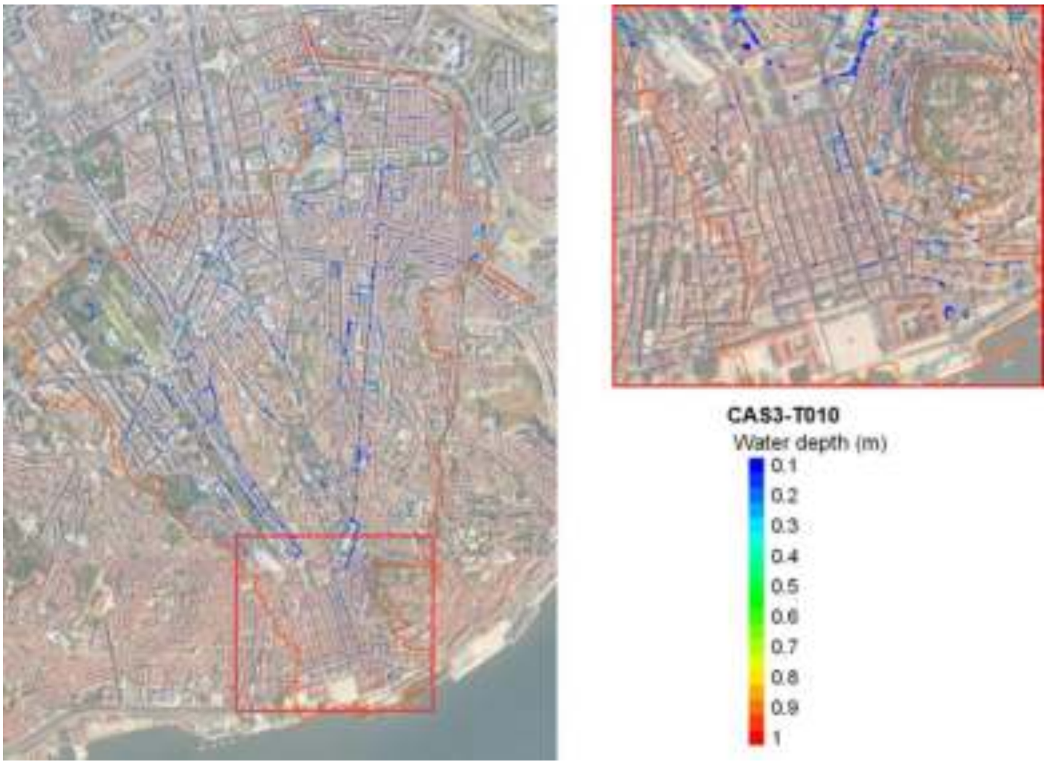


Figure 121. CMSB results: water depth at critical time for CAS3-T010.

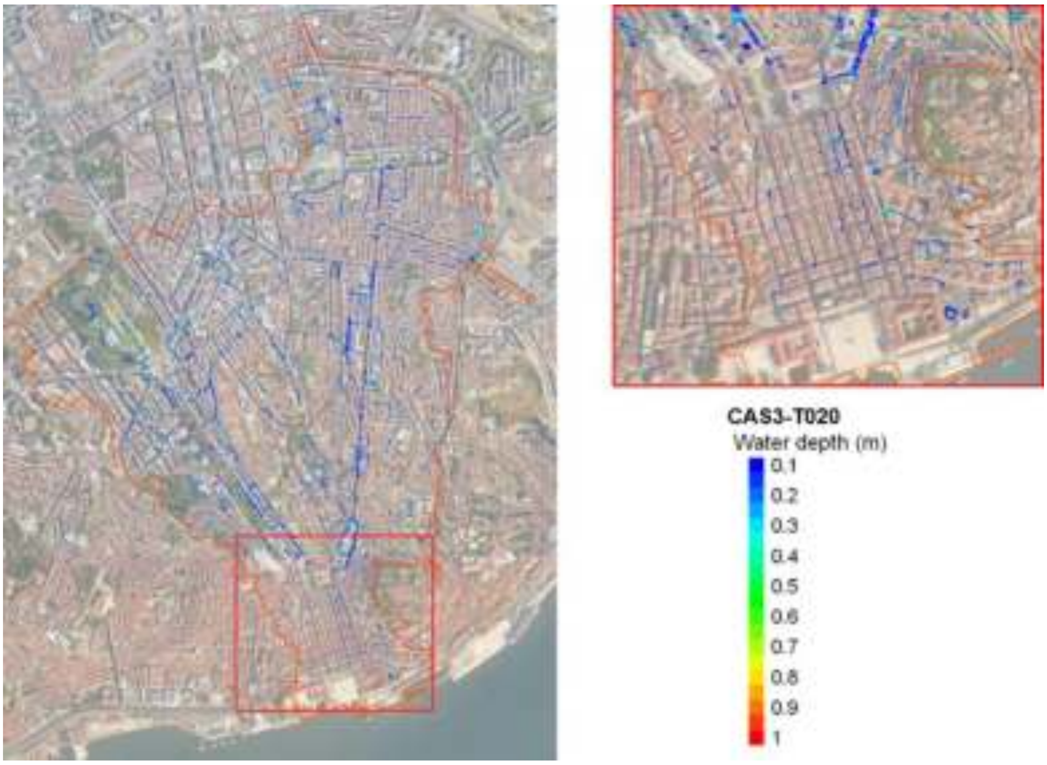


Figure 122. CMSB results: water depth at critical time for CAS3-T020.

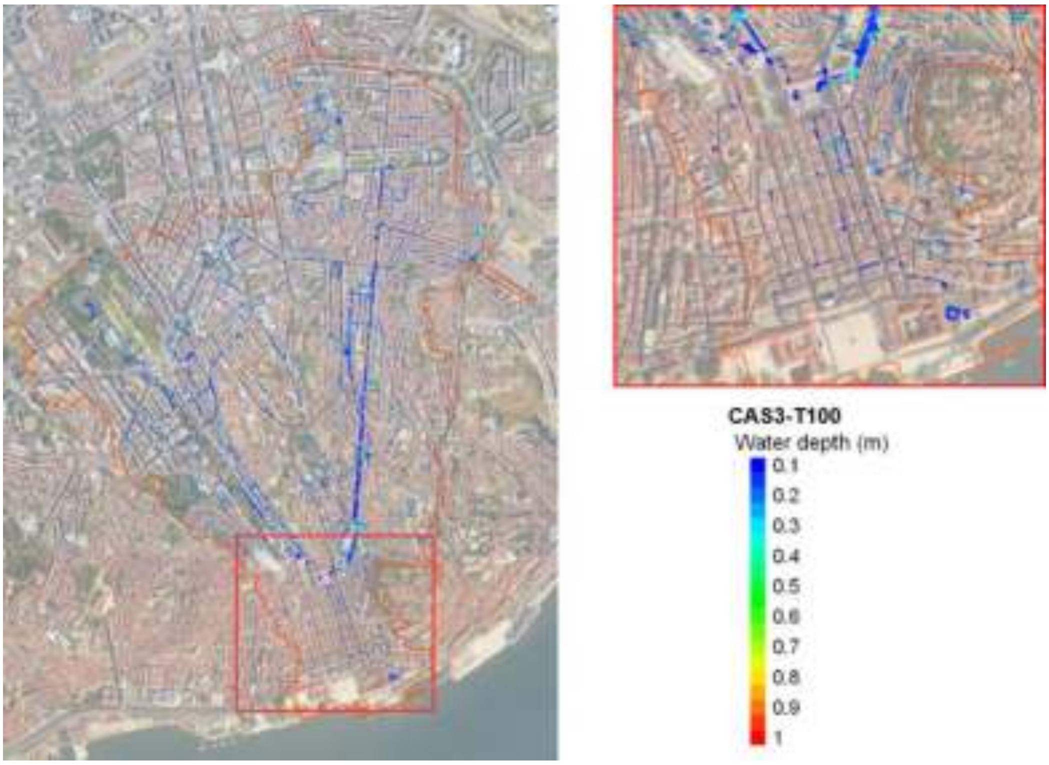


Figure 123. CMSB results: water depth at critical time for CAS3-T100.

The main effects of construction of the diversion tunnels, as provided by the simulation results, are the increase of the carrying capacity at the downstream sewers, has obtained by the 1D GIS Model simulations. Nevertheless, in some cases, considerable water depths still occur due, probably due to limited capacity of inlet devices to deal with the generated runoff. This is the case of main streets, to which the generated runoff flows (due to the topographic characteristics), that are still prone to have some water accumulation at the surface.

The main differences to the BAU situation are on two main areas: (i) lower zones of Largo do Regedor, Rossio and Praça da Figueira, with lower flooding due to the capacity of the drainage system to accommodate the overland flows, collected by the inlet devices located in these "sag" locations; (ii) improvements in Praça do Comércio and surrounding areas, with reduction of overflow to the surface due to the surcharge of the drainage system.

The results of the flooding water depth hazard, for BAU and CAS3 situations, are presented in Figure 124, with the quantitative variation in Table 48. These results include only the drainage catchments areas located downstream from the diversion tunnels.

Assessment of flooding hazard to pedestrians. The flooding hazard to pedestrians' assessment uses the methodology as in Deliverable 2.3 (Russo, 2019). The results are in Figure 125 and Figure 126, for BAU and CAS3 situations, with quantitative variation in Table 49. There is a slight decrease for the 10-year return period, more noticeable for the 20 and 100-year return period rainfalls, reaching an increase in the area classified with low pedestrian hazard class of about 10%.

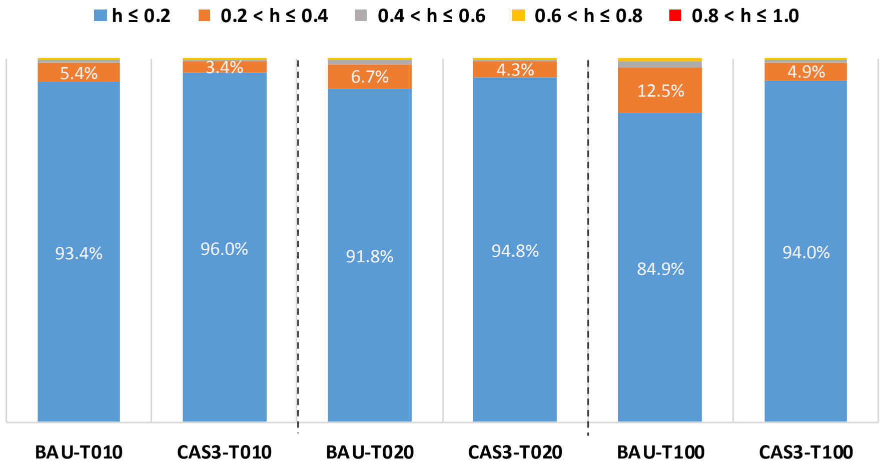


Figure 124. Flooding water depth hazard assessment: results for BAU and CAS3.

Table 48. Flooding water depth hazard assessment: comparison between BAU and CAS3.

Hazard class	Return period		
	T010	T020	T100
Very low	+2.6%	+3.1%	+9.1%
Low	-2.0%	-2.4%	-7.6%
Moderate	-0.6%	-0.5%	-1.0%
Significant	0.0%	-0.1%	-0.5%
Extreme	0.0%	0.0%	0.0%

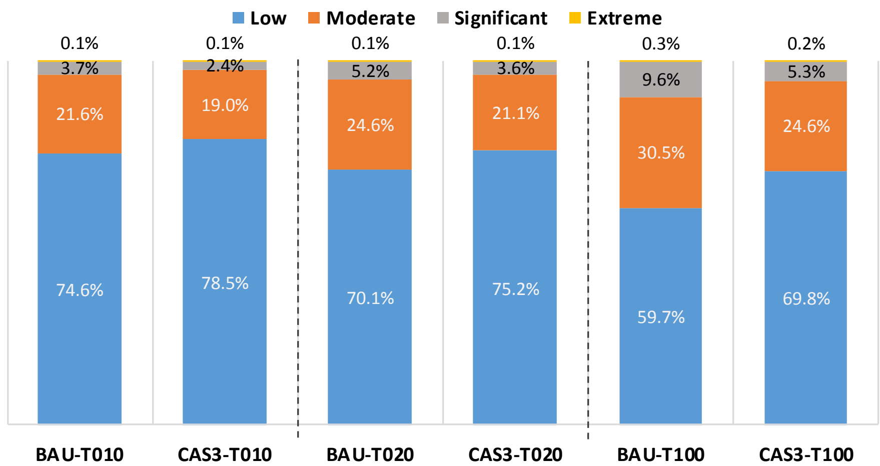


Figure 125. Pedestrian hazard assessment: results for BAU and CAS3.

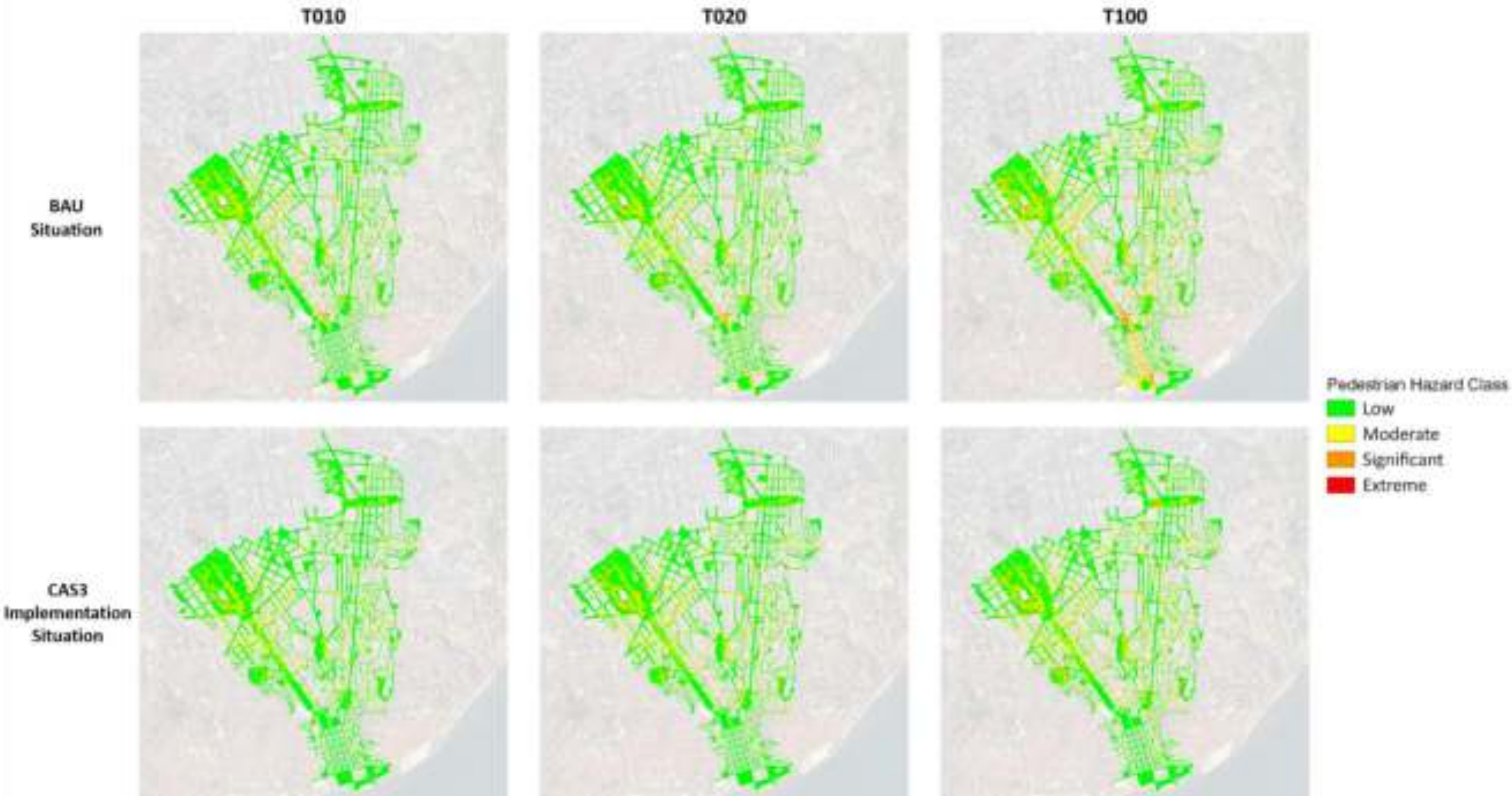


Figure 126. Pedestrian hazard maps overview for BAU and CAS3.

Table 49. Pedestrian hazard assessment: comparison between BAU and CAS3.

Pedestrian Hazard Class	Return period		
	T010	T020	T100
Low	+3.8%	+5.1%	+10.2%
Moderate	-2.6%	-3.5%	-5.9%
Significant	-1.2%	-1.5%	-4.2%
Extreme	0.0%	0.0%	-0.1%

Assessment of flooding hazard to vehicles. Using the methodology as in Deliverables 2.2 and 2.3 (Russo, 2018a) (Russo, 2019), the results of the assessment of flooding hazard to vehicles, for BAU and CAS3 situations, are presented in Figure 127 and Figure 128, and the respective quantitative variation is stated on Table 50.

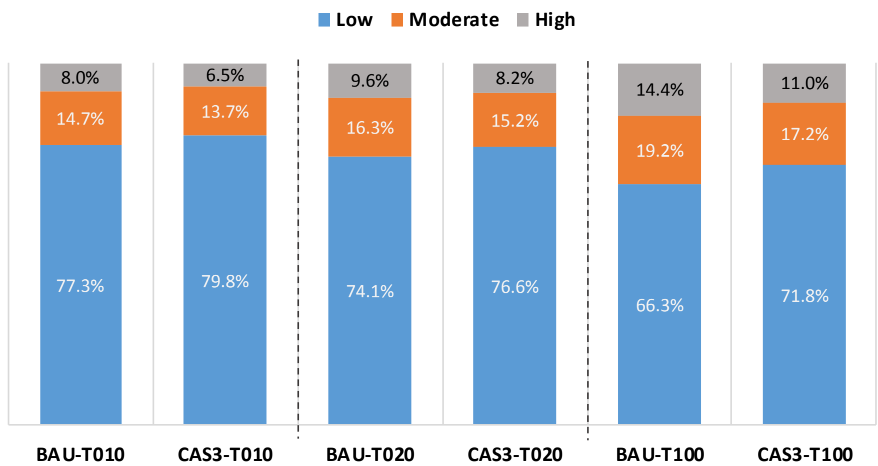


Figure 127. Assessment of hazard to vehicles: results for BAU and CAS3 situations.

Table 50. Assessment of hazard to vehicles: comparison between BAU and CAS3 situations.

Hazard to Vehicles Classes	Return period		
	T010	T020	T100
Low	+2.4%	+2.5%	+5.5%
Moderate	-1.0%	-1.1%	-2.0%
High	-1.5%	-1.4%	-3.5%

The results regarding the hazard to vehicles follow the tendencies of the previous assessed hazards, with a slight increase in all the simulated return periods.

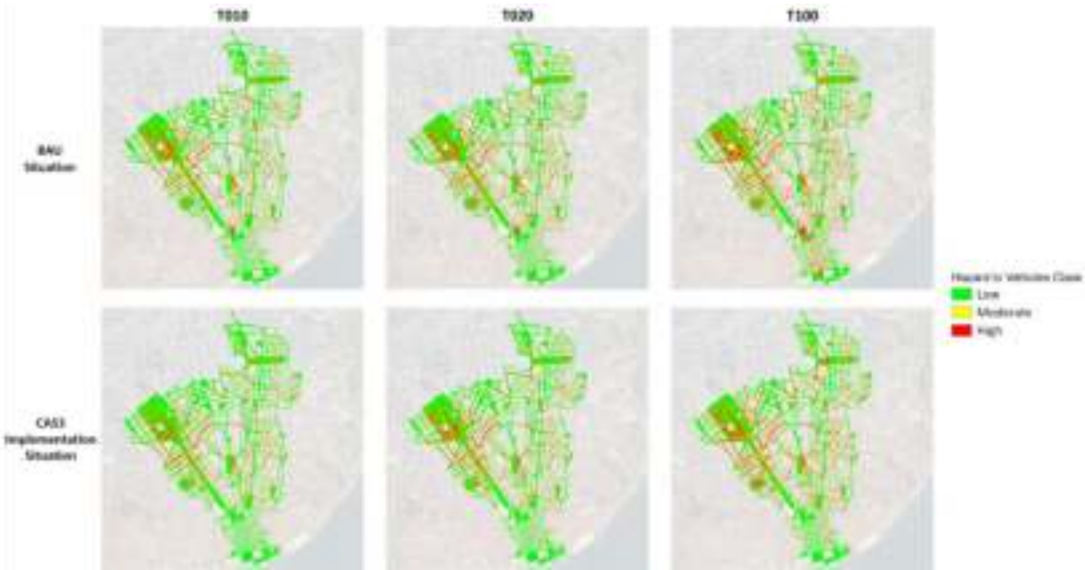


Figure 128. Hazard to vehicles maps overview for BAU and CAS3 situations

4.4 Traffic sector

4.4.1 Introduction and summary of specific climate hazards and risk for the traffic sector

As presented in Deliverables 2.2 and 2.3 (Russo, 2018a) (Russo, 2019), a GIS based surrogate model approach has been used. The 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.

The outcomes include exposure and transport sector critical components for each scenario analyzed and estimation of broad impacts on the service for current situation. Lisbon road network hierarchical five levels classification, based on attributes of roads, was used.

Critical components for functioning of road and rail network, relevant tunnels and level crossings were also identified. 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 classification is a function of type, volume and supply of transports, as well as of the number of passengers.

Vulnerability assessment uses as criteria the hierarchical classification of the roads and interfaces.

Regarding the tide induced flooding, results from recent studies (Antunes, Rocha and Catita, 2017) allow to conclude that previous results, used for analysis of current situation, were conservative and correspond broadly to the updated 2100 scenario.

Both citywide and Lisbon downtown catchments were used, with the corresponding data for the indicators available from the hydraulic modelling.

Evaluation of exposure of transports infrastructures and services for different levels of hazards is based on selected metrics (Table 51, Figure 129 and Figure 130, for current situation). The vulnerability is assessed using as criteria the hierarchical classification of the roads and interfaces. The vulnerability can be evaluated from the hierarchical classification of the roads and interfaces.

Table 51: Road and rail networks exposure and vulnerability metrics to flooding hazards (CS).

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

Globally, for CS, 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 (Russo, 2019).

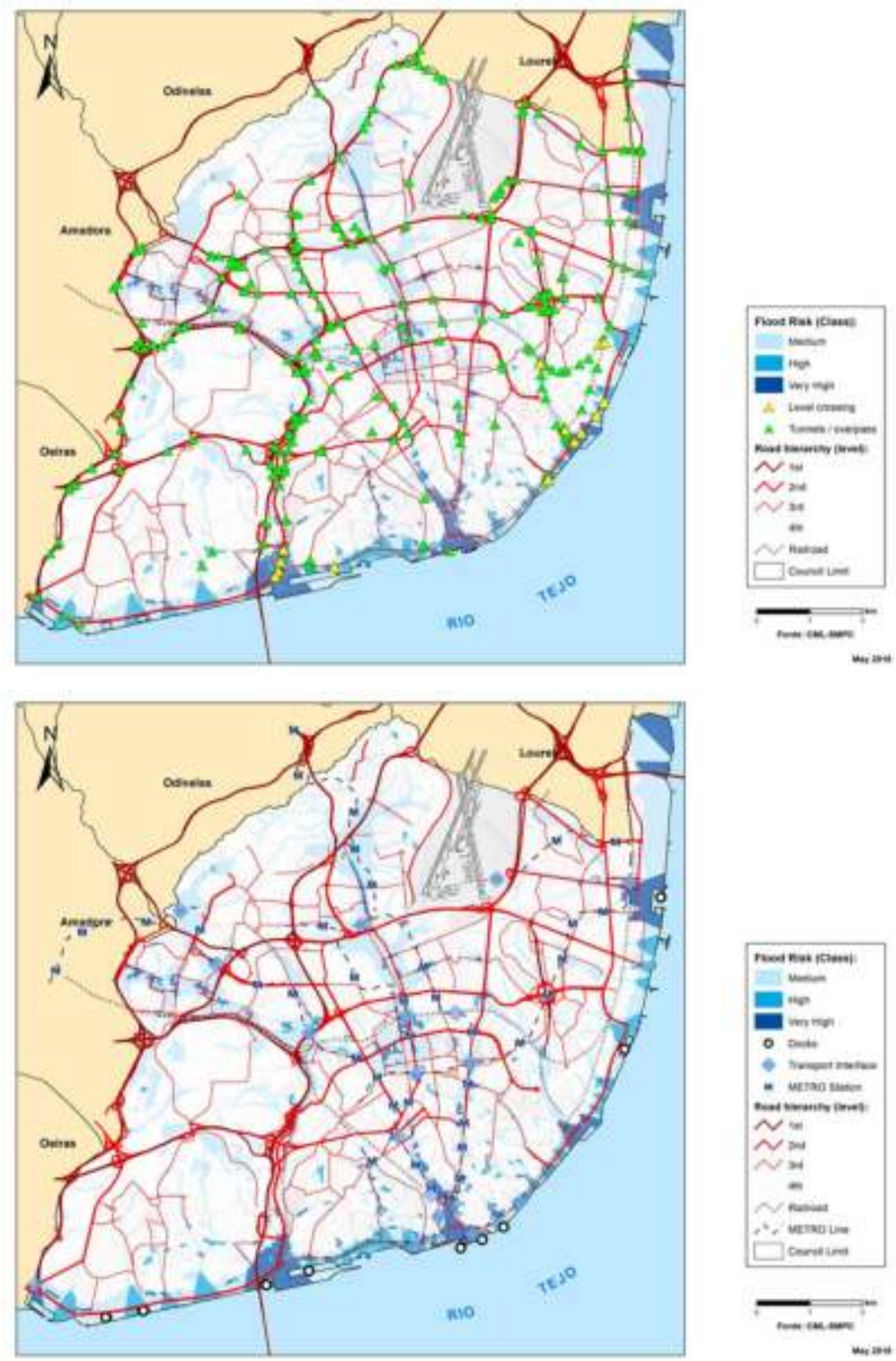


Figure 129: Results for exposure and vulnerability to rainfall induced flooding: mapping for transport networks and interfaces.

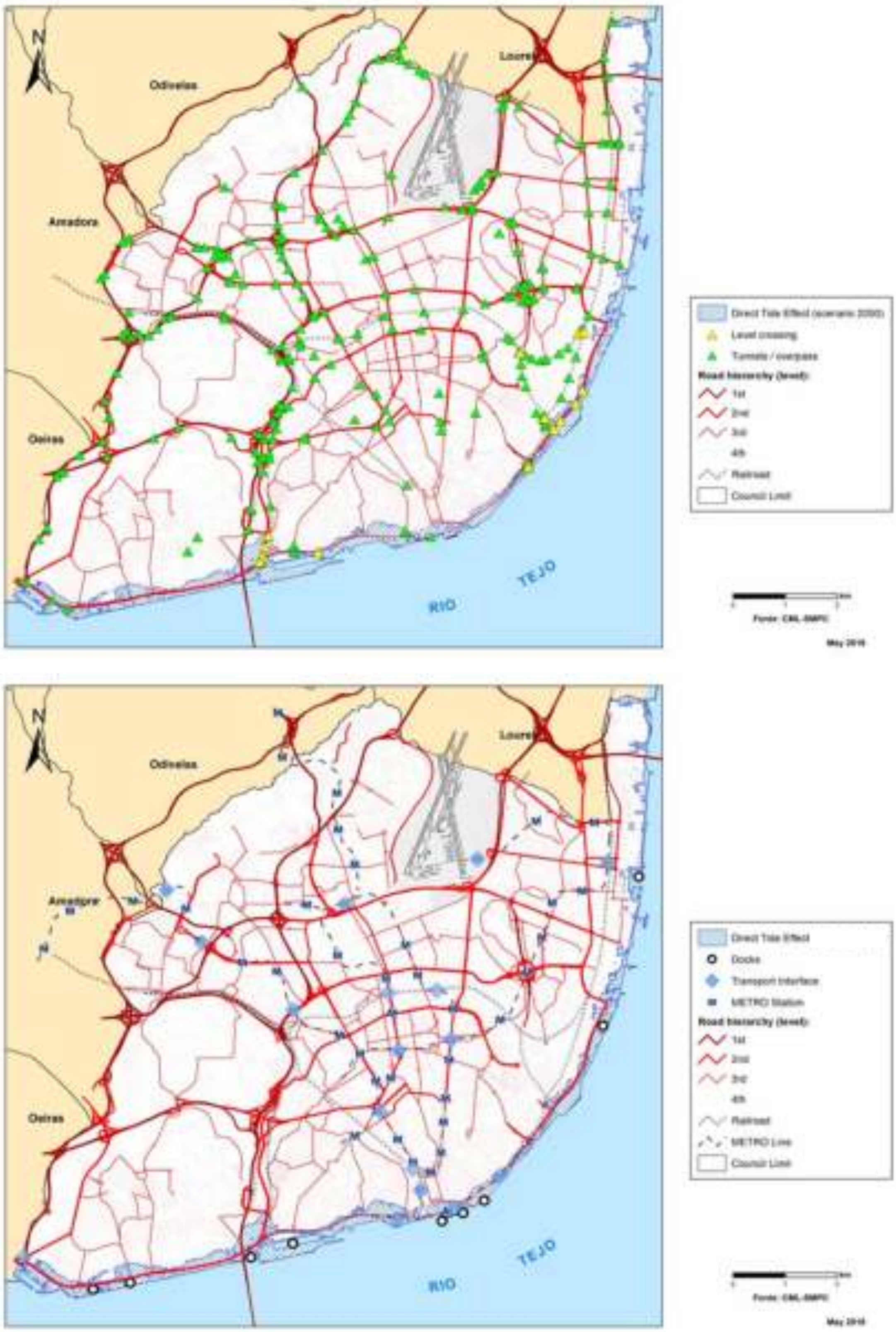


Figure 130: Results for exposure and vulnerability to estuary level induced flooding: mapping for transport networks and interfaces.

Rain-induced flooding level was not assessed for the whole city and the differences for Lisbon downtown are not very significant, with small aggravation only for the 100-years return period. As presented in Deliverable 2.3 (Russo, 2019), for the downtown catchment J and L, main differences from current situation to BAU scenarios, i.e. BAU-CD (Table 52) lead to variations above 5% in length just obtained for local situations for T100, for water level up to 0.4 m and global values are relatively stable.

Table 52: Downtown road networks metrics to flooding hazards: comparison of BAU and CS.

Network type/class		Δ BAU-CS on length affected by rain induced flooding (% class)				
	Length (km)	Flooding level >	0.2 m ≤ d < 0.4 m	0.4 m ≤ d < 0.6 m	0.6 m ≤ d < 0.8 m	0.8 m ≤ d < 1.0 m
Road 2nd level	12.9	T010	2.63	0.22	-0.01	0.00
		T020	3.17	0.22	0.00	0.00
		T100	5.99	0.23	0.04	0.00
Road 3rd level	18.1	T010	3.50	0.43	0.07	0.03
		T020	4.36	0.70	0.05	0.04
		T100	8.80	1.10	0.35	0.01
Road 4th / 5th level	123.1	T010	1.39	0.12	-0.02	-0.02
		T020	1.23	0.16	0.06	0.00
		T100	1.91	0.22	0.11	0.02
ROAD TOTAL	**154.1**	**T010**	**0.68**	**0.03**	**-0.04**	**-0.02**
		T020	**0.40**	**0.06**	**0.03**	**0.00**
		T100	**0.71**	**0.02**	**0.05**	**0.01**

more than 5% increase ; 1% to 5% increase; stable; more than 1% decrease

For tide induced values for the two scenarios (2050, 2100), according to Antunes *et al.* (Antunes, Rocha and Catita, 2017), results also show little variations for roads Table 52, with no exposure for railways.

4.4.2 Adaptation strategies, measures and design criteria

Measures modelled were only related to flooding and the related hazards and were not specifically focused on mobility and transport sectors. With available data and models, only CAS3 is evaluated in this sector.

4.4.3 Modelling of adaptation strategies, measures to achieve hazard and risk reduction

Considering the results of the hydraulic simulations for the downtown catchments J and L, in Table 53 the impacts on transport infrastructure are given. For the whole city, the simplified approach does not provide results compatible with this assessment. The strategy has an effect of somehow compensating the effect of climate change since the variations to current situation are not relevant.

Comparing the global results for downtown catchments J and L obtained for CS, BAU and CAS3 (Table 54), in terms of total area flooded, variations are below 10% for all return periods and situations. Variations are considered to be within the error margins of the approach.

Table 53: Downtown road networks metrics to flooding hazards: comparison of CAS3 and CS.

Network type/class		Δ BAU-CS on length affected by rain induced flooding (% class)				
	Length (km)	Flooding level >	0.2 m ≤ d < 0.4 m	0.4 m ≤ d < 0.6 m	0.6 m ≤ d < 0.8 m	0.8 m ≤ d < 1.0 m
Road 2nd level	12.9	T010	◄► 0.03	◄► 0.00	◄► -0.01	◄► 0.00
		T020	◄► 0.04	◄► 0.01	◄► 0.00	◄► 0.00
		T100	◄► -0.02	◄► 0.01	◄► 0.00	◄► 0.00
Road 3rd level	18.1	T010	◄► -0.16	◄► 0.01	◄► 0.01	◄► -0.01
		T020	◄► -0.14	◄► -0.05	◄► 0.00	◄► 0.00
		T100	◄► -0.55	◄► -0.13	◄► -0.04	◄► 0.00
Road 4th / 5th level	123.1	T010	◄► -0.24	◄► -0.23	◄► -0.02	◄► -0.02
		T020	◄► -0.32	◄► -0.06	◄► -0.05	◄► 0.00
		T100	▼ -2.11	◄► -0.27	◄► -0.13	◄► 0.02
ROAD TOTAL	**154.1**	**T010**	◄► **-0.36**	◄► **-0.21**	◄► **-0.03**	◄► **-0.02**
		T020	◄► **-0.43**	◄► **-0.106**	◄► **-0.05**	◄► **0.00**
		T100	▼ **-2.68**	◄► **-0.39**	◄► **-0.17**	◄► **0.02**

▲ more than 5% increase ; ▲ 1% to 5% increase; ◄► stable; ▼ more than 1% decrease

Table 54: Downtown road networks metrics to rain induced flooding hazard: global results for CS, BAU and CAS3.

	CS_flood (Km)	CS_flood (%)	BAU_flood (Km)	BAU_flood (%)	CAS3_flood (Km)	CAS3_flood (%)
T010	6.1	4.0%	7.1	4.6%	5.2	3.3%
T020	7.5	4.9%	8.3	5.4%	6.6	4.3%
T100	12.7	8.2%	13.9	9.0%	7.7	5.0%

4.5 Waste sector

As detailed in Deliverable 2.2 (Russo, 2018a) and (Russo, 2018b), the approach to model the effect of flooding events on wastes management in Lisbon takes into consideration the events recognized as disruptive to the city and the data available. The effects of the failure of the drainage system causes disruptions on waste collection components including bins overturn, dragging, floating, filling with water and damage. Additionally, it 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, with subsequent spread of wastes on streets, blockages of inlets and other drainage components. Accumulation of debris on streets requiring deep cleaning before resuming service. Since the use of a mechanism to avoid movement of bins permanently placed on the streets is almost generalized, these problems are limited in number.

The approach adopted for the current situation to the whole city (Deliverable 2.2) (Russo, 2018a), using historical data, is not feasible for consideration of climate change scenarios since characterization of flooding hazard is not available. Therefore, given that this information from modelling is only available for the downtown catchments J and L, only this area is analysed for all situations (CS, BAU and CAS3) to assess the exposure and the vulnerability of waste collection to flooding. The approach for wastes services and components is a GIS-based surrogate model making use of available information and results from flooding.

For current situation, a summary of the results of Deliverable 2.2 (Russo, 2018a) are presented for the whole city. The surrogate model to estimate impacts on solid wastes is detailed in Deliverable 2.2 (Russo, 2018a). The outcomes include exposure metrics for locations and bins for each scenario analysed. For climate change scenarios, the analysis of the effects of CC scenarios for the downtown catchments J and L is carried out using the results of the simulations using the 1D/2D CMSB model.

The available collection types in Lisbon are:

i. large public bins (bring banks) – several bins 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).

For catchments J and L not all types exist, distribution being indicated in Figure 131.

Components not yet restrained with a support to restrict movement are critical. These remaining situations are in limited numbers and not localized by a specific criteria. Improvement in terms of resilience can be achieved by upgrade those components localized in areas more exposed to flooding using the results of this surrogate model. The door-to-door bins are also exposed when placed outdoors, even if only for a limited time per week.

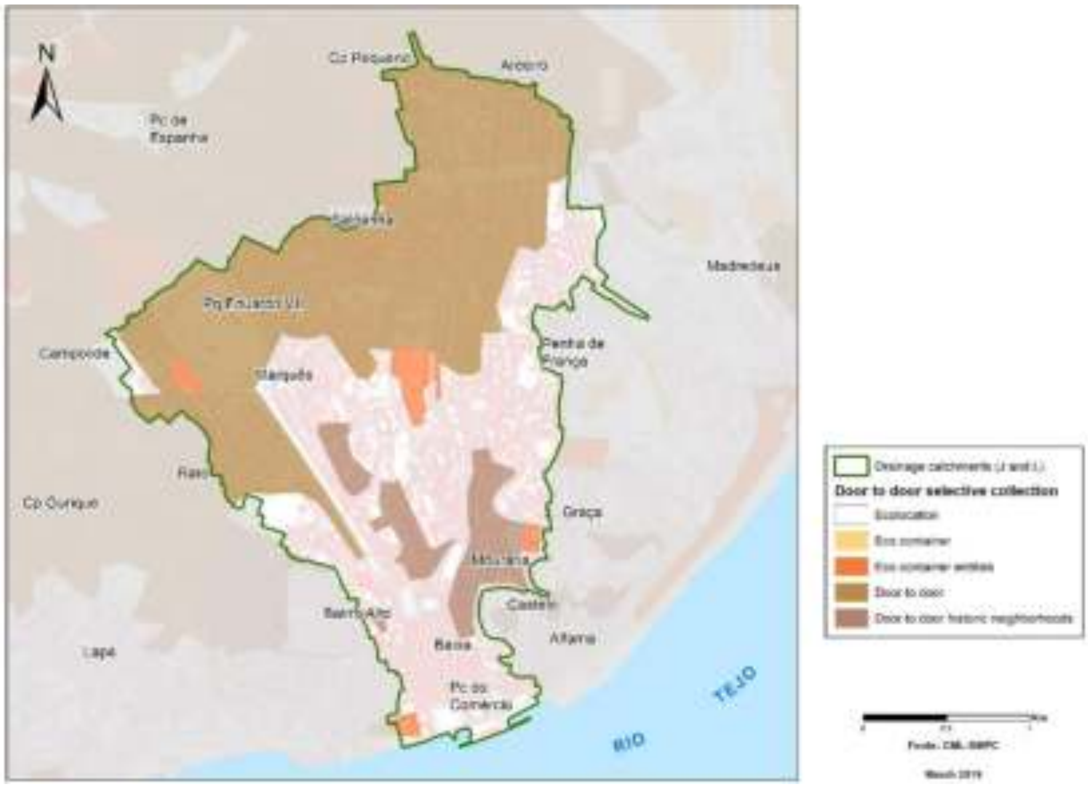


Figure 131: Zoning of types of wastes collection systems at downtown catchments J and L.

4.5.1 Introduction of specific climate hazards and risk for the waste sector

Assessment for the whole city of Lisbon

Globally, in Lisbon, there are 55,237 collection locations and 204,004 bins. These are serving the 547,733 inhabitants, 243,892 families, 52 500 buildings and 350,000 households. The summary of results for the whole city allow to conclude about current exposure of wastes infrastructures and services for different levels of hazards using selected metrics (Table 55). From the results, only 20% of the locations and 22% of bins are exposed to flooding in current situation. The "door-to-door" system comprehends a large number of locations and bins, respectively, 64% and 82% of total installed. However, globally, only around 20% are exposed areas.

For door-to-door modes, vulnerability is low since bins are outdoor for a limited time of few hours per week, depending on type of waste. A significant number of the bins permanently outdoors and exposed to flooding has a locking system, which limits the movement of the bins, 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 stabilization or restraining mechanisms, as well as option for underground alternatives. The results indicate a significant residence to flooding of waste collection in Lisbon.

Table 55: Wastes components exposure metrics to flooding hazards: summary of citywide results.

Type		Number affected by rain induced flooding				Number affected by tide induced flooding
	Total n. locations / n. bins	Flooding risk class ->	Moderate	High	Very high	
Total locations	55238	n. %	11208 20	2343 4	5275 10	1533 3
Total bins	204004	n. %	45508 22	8583 4	15579 8	3033 2

Assessment for Lisbon downtown catchments J and L

Globally, in Lisbon downtown catchments J and L, there are **12,357** collection locations and **43,075** bins. Summary of results of exposure to flooding of locations and bins are in Table 56 and Table 57, respectively, for rain induced flooding and tide induced flooding.

Table 56: Downtown results for rain induced flooding: locations and bins.

Network type/class		CS components affected by rain induced flooding (%class)				
	Total n. locations / n. bins	Flooding level >	**0.2 m ≤ d < 0.4 m**	**0.4 m ≤ d < 0.6 m**	**0.6 m ≤ d < 0.8 m**	**0.8 m ≤ d < 1.0 m**
Total locations	12357	**T010**	**2.0**	**0.7**	**0.1**	**0.0**
		T020	**2.9**	**0.5**	**0.2**	**0.0**
		T100	**6.6**	**0.9**	**0.4**	**0.0**
Total bins	43075	**T010**	**1.3**	**0.6**	**0.0**	**0.0**
		T020	**2.2**	**0.3**	**0.2**	**0.0**
		T100	**5.2**	**0.6**	**0.3**	**0.0**

In these two catchments, the "door-to-door" is predominating in number of locations (95%) and bins (98%). As mentioned previously, in this collection mode, bins exposure is just some hours per week and building dwellers are responsible for the bins. For other types of collection mode, it is relevant to ensure installation of the locking system to all bins, to limit the movement of the bins, adding to the stability of these components when subject to flooding or overland flow.

Very few bins are exposed to higher flooding water levels, globally less than 1% locations or bins above 0.4 m and up to 7% locations and 5% bins for water level lower than 0.4 m. Numbers increase slightly with the return period. Comparing with the results for the whole city the exposure is significantly lower.

For tide induced flooding, only elements in the "door to door" waste collection mode are exposed, up to 2% (2050) and (2100) locations and around 1% (2050) and 3% (2100) bins.

Table 57: Downtown wastes components: results for 2050 and 2100.

Waste colletion type /class	**Total class**		**2050 scenario**	**2100 scenario**
Total locations (n.)	**12357**	-	219	508
Total bins (n.)	**43075**	-	611	1269

Main differences from current situation to climate change scenarios, i.e. BAU-CD for wastes collection components are presented in Table 58. Globally, variations are very low and values not considered significant since are below 1%. For the modes of collection for “door-to door”, the predominant mode in these catchments, variations are below 1%. For the remaining modes, representing low numbers in locations and bins, differences are observed for “Glass aboveground” (variations up to 4%), for “Ecoilha underground” (variations up to 2.5%) and for “Ecoponto aboveground” (variations are up to 5%).

For tide induced values for the two scenarios (2050, 2100), according to Antunes *et al.* (Antunes, Rocha and Catita, 2017), only elements in the “door to door” waste collection mode are exposed, up to 2% (2050) and (2100) locations and around 1% (2050) and 3% (2100) bins.

Table 58: Downtown wastes collection exposure to flooding hazards: Δ BAU-CS (locations or bins) affected by rain induced flooding (% class).

Type	N.	Flooding level >	0.2 m ≤ d < 0.4 m	0.4 m ≤ d < 0.6 m	0.6 m ≤ d < 0.8 m	0.8 m ≤ d < 1.0 m
Total locations	**12357**	**T010**	0.76	0.02	-0.05	0.00
		T020	0.59	0.04	0.00	0.00
		T100	0.82	0.01	0.00	0.00
Total bins	**43075**	**T010**	0.47	-0.13	-0.04	0.00
		T020	0.46	0.07	0.00	0.00
		T100	0.60	0.34	0.00	0.00

▲ more than 5% increase ; ▲ 1% to 5% increase; ◀▶ stable; ▼ more than 1% decrease

4.5.2 Adaptation strategies, measures and design criteria

Measures modelled were only related to flooding and the related hazards and were not specifically focused on mobility and transport sectors. With available data and models, only CAS3 is evaluated in this sector.

4.5.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

Considering the results of the hydraulic simulations for the downtown catchments J and L, in Table 59 the impacts on waste sector are given. The differences are irrelevant between CAS3 and current situation.

For the whole city, the simplified approach does not provide results compatible with this assessment. The strategy has an effect of somehow compensating the effect of climate change since the variations to current situation are not relevant.

Table 59: Downtown wastes collection exposure to flooding hazards: Δ CAS3-CS (locations or bins) affected by rain induced flooding (% class).

Type	N.	Flooding level >	Sub-total (m)	0.2 m ≤ d < 0.4 m	0.4 m ≤ d < 0.6 m	0.6 m ≤ d < 0.8 m	0.8 m ≤ d < 1.0 m
Locations	12357	T010	12095	0.58	-0.11	-0.43	-0.05
		T020	12045	1.12	-0.76	-0.19	-0.19
		T100	11866	3.97	-3.41	-0.57	0.00
Bins	43075	T010	42379	0.37	0.10	-0.43	-0.04
		T020	42126	0.58	-0.29	-0.09	-0.21
		T100	41566	2.62	-2.23	-0.39	0.00

more than 5% increase ; 1% to 5% increase; stable; more than 1% decrease

4.6 Electrical sector

4.6.1 Introduction of specific climate hazards and risk for the urban drainage sectors

The electrical sector represents an essential economic activity for the society, which can make a substantial contribution to climate change mitigation and adaptation. In a city such as Lisbon, the distribution of electricity is recognised as a relevant economic activity by itself, but also contributing to the adaptation to climate risks of other sectors given the dependency of infrastructures and costumers. Naturally, EDP has been working on the reliability of the service. Within Lisbon, the electrical grid is diverse and composed by different assets regarding voltage, with reference for primary substations, secondary substations and underground cables. In Lisbon, with a quality of service zone type A, the electrical grid is composed by (Figure 132):

- Primary substations: 27
- Secondary substations: 4,288
- Number of clients: 549,543

Figure 132: Electrical grid (HV and MV) in Lisbon Municipality.

As a Distribution System Operator (DSO), for EDP Distribuição it was important identify and analyse which system assets were or can be affected by climate change scenarios and for which it is relevant and critical to implement mitigation and adaptation strategies that can contribute to prevent and reduce impacts when a disruption occur, taking into account the specific in context.

The methodology adopted in RESCCUE is based on the identification of the assets that are vulnerable and exposed to the selected climate change scenarios studied, essentially in high (HV) and medium voltage (MV), as reported in Deliverables 2.2 (Russo, 2018a) and 2.3 (Russo, 2019).

The information obtained for the scenarios allowed defining adaptation strategies focusing on primary and secondary substations, further increasing the already resilient system.

Based on a resilience approach, by improving the electrical infrastructure regarding climate change scenarios, the DSO can improve the quality service in those exposed areas, as well as continue providing an essential service to all society.

All strategies and its specific measures possible to be developed to achieve resilience goals of the electrical grid are assessed using models and current economic indicators, such as cost/benefit approach, as appropriate and applicable. The results help to evaluate the benefits to quality service scope, given that all investments must be approved by the regulator and should be included in PDIRD investment plan (Plano de Investimento na Rede de Distribuição).

As presented in previous deliverables , Deliverables 2.2 (Russo, 2018a) and 2.3 (Russo, 2019), flooding hazards characterized by using hydraulic modelling, allowed to identify how the electrical sector in Lisbon could be affected. The distribution infrastructure is mostly underground and vulnerability was found to be low even when located in areas where flooding events occur periodically.

In the downtown areas of catchments J&L there are 2 underground primary substations, but only one is relevant for this scope, since the other is on the top of a hill and by the previous modelling analysis confirmed that is not exposed to flood-related hazards.

The main areas in Lisbon comprised by current scenarios and BAU scenarios, are in the downtown area, especially in Rossio, namely Praça da Figueira, and in Praça do Comércio. In both scenarios, the impact in the electrical infrastructure are nearly the same, still the assets in those areas are similar and, in case of a failure, the measures already implemented, following some flooding events, reduced the vulnerability and increased the capacity to respond to any outage with the same causes. Comparing the scenarios, and combine it with historical data, it was possible to identify which assets are more exposed to climate change flood-related scenarios.

As referred in Deliverable 3.4 (Evans, 2019), Lisbon has a high redundancy of service for high and medium voltage, because it is classified as a Quality Zone A. The response times in case of a disruption are more demanding then for other Quality of Service zones and, even for climate change scenarios, the response and recovery of the electrical grid is stable and resilient.

Combining all the historical data gathered with the simulations made in the previous deliverables mentioned above, it was possible to identify which specific assets should have strategies to minimize the risk of failure by implementing the adaptation measures in the relevant assets of electrical infrastructure to face context-specific climate change scenarios.

4.6.2 Adaptation strategies, measures and design criteria

Adaptation strategies and measures must be adjusted to the infrastructure, to the asset and to the location, to have a suitable response to the impacts caused by flood. Therefore, each strategy needs to be adapted to each situation. The strategies specific for the electrical sector included in Table 32 are *S018Lisbon - Architecture integration/solutions adaptations for urban electrical infrastructure to face overland flows or coastal water overtopping* and *S019Lisbon -*

Building protections for urban electrical infrastructure, exposed to estuarine flood. The corresponding measured are in Table 60.

Table 60: Strategies and measures considered for the electrical sector.

ID	Strategy / measures
S018Lisbon	**Architecture integration/solutions adaptations for urban electrical infrastructure to face overland flows or coastal water overtopping**
M010FLOOD	Install flood proof fencing
M005FLOOD	Learn from real-life flooding by recording and investigating events
M013FLOOD	Emergency response plans and procedures
M001SLRISE	Build riverside flood defence walls
S019Lisbon	**Building protections for urban electrical infrastructure, exposed to estuarine flood**
M010FLOOD	Install flood proof fencing
M005FLOOD	Learn from real-life flooding by recording and investigating events
M013FLOOD	Emergency response plans and procedures
M001SLRISE	Build riverside flood defence walls

The strategies applied by EDP Distribuição, were included in Deliverable 5.2 (Martínez - Gomariz, 2019), and can be replicated in any similar situations (assessed in context-specific). Based on previous studies, these measures are derived from lessons learnt from historical events where the following measures were implemented (Figure 133):

- increasing pumping capacity of water pumps;
- increasing the number of water pumps;
- building fences on the surface around air entrances of the underground substations to prevent water from entering.

The measures can be complementary, improving the possible compatibility between sustainability and resilience of the electrical infrastructure. The measures were implemented especially in the primary substations that have historical data of floods as presented in Deliverable 3.3 (Evans, 2017).

Water pumps | Fencing air vents on surface

Figure 133: Measures to face flooding hazards.

The additional pumping capacity prevents water from accumulating at the premises of the underground primary or secondary substation. On the other hand, some of these pumps, can has a garbage disposal system to crush any waste that could otherwise reduce the efficiency of the pumps. Additionally, this strategy was adopted generically for underground substations, designed for each case (site and asset specific).

The underground substations need ventilation to cool power transformation equipment and have vents on the surface, which can be an entrance to water inside the asset. The installation of fences around the vents, limits water entry effectively. The application at Lisbon downtown can still be improved by integrating the fences in terms of urban or landscape architecture, especially in cities.

A primary substation is one of the most important assets of the electrical grid, therefore, when applying strategies to reduce the impact of a disruption, improving infrastructure resilience, the DSO is assuring a better service for society.

These adaptation strategies are intended to prevent floods impact, especially those with higher return periods that can cause more impact to the electricity supply.

After analysis of the results for the whole city, another sub-station was found to be exposed to estuary water level hazard (Figure 134). Therefore, the strategies S018 and S019 was selected for application to this facility. The analysis and design is ongoing during the current phase of the project, taking into consideration also the integration in the surrounding landscape.

Figure 134: Sub-station where strategy implementation is planned to prevent flooding.

4.6.3 Modelling of adaptation strategies and measures to achieve hazard and risk reduction

The implementation of previous strategies in the primary substation increases the resilience of the infrastructure regarding flood events.

Since the implementation of the selected strategies downtown, no flooding events causing outage on the electricity supply were registered in the substation.

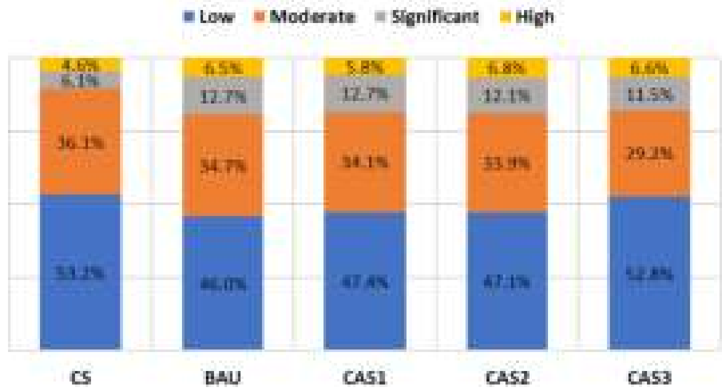
The simulation of the scenarios provided by the models with these strategies already implemented, confirm that it is not predictable a failure of service, therefore it is expected that according to the scenario the electrical infrastructure can face a flood event in the studied area, assuring the electricity supply (Figure 135).

Figure 135 - Electrical grid configuration by adopting risk reduction strategies.

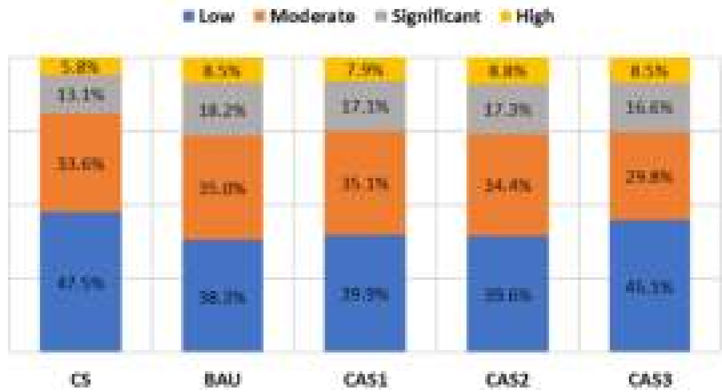
4.7 Conclusions about adaptation strategies implementation for Lisbon Research Site

Urban drainage sector

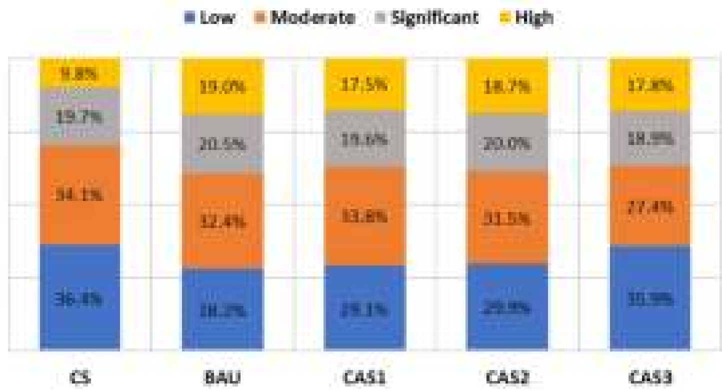
Globally, the results of the assessment of the strategies using mathematical modelling, for the performance metric use of sewer capacity, are compared side-by-side in Figure 136 and Figure 137, respectively, distribution of sewers per classes for each situation and variation from current situation (CS).



(a) Use of sewer capacity: results for T010



(b) Use of sewer capacity: results for T020

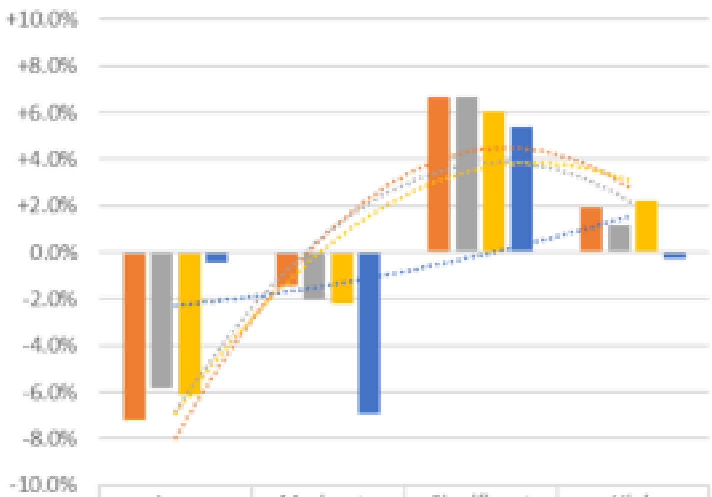


(c) Use of sewer capacity: results for T100

Figure 136. Use of sewer capacity: results for CS, BAU and CAS situations.

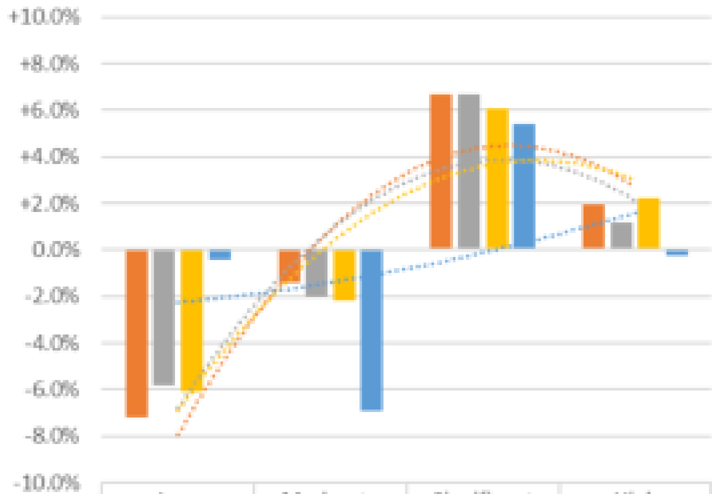
Interpretation of results is facilitated by Figure 137 where the trend lines are just used as a support to the reader. Global performance decreases when bars are higher to the right and to positive values; conversely bars higher to negative values and to the left represents a trend of improvement.

Therefore, climate scenarios (BAU) result in a global reduction of performance for all return periods simulated. The strategy CAS1 has potential to compensate slightly the CC effect. CAS2 has a significant local effect but overall performance is minor. Also CAS3 has a stronger effect locally than globally, but the impact in the global performance is significant. Nevertheless, the values are relatively low. Current situation is not favorable and variations obtained for the scenarios of CC are likely lower than the errors associated with the model used. Limitations of this very simplified model used as well as lack of data on effective flow capacity must be taken into account.



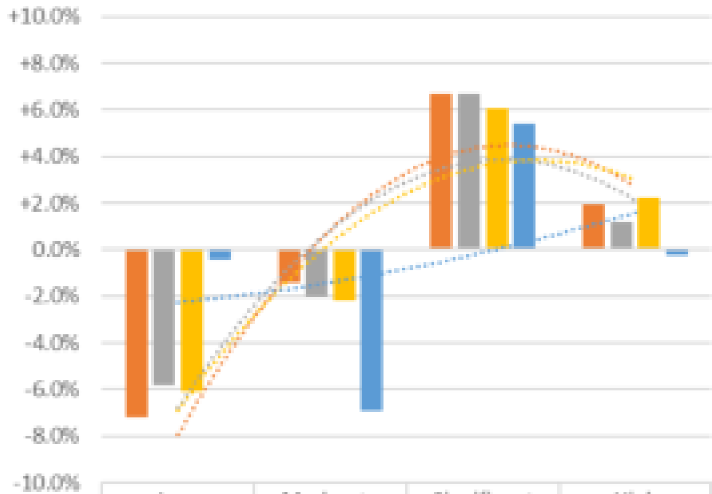
	Low	Moderate	Significant	High
BAU-T010	-7.2%	-1.4%	+6.7%	+1.9%
CAS1-T010	-5.8%	-2.0%	+6.7%	+1.2%
CAS2-T010	-6.1%	-2.2%	+6.1%	+2.2%
CAS3-T010	-0.4%	-6.9%	+5.4%	-0.3%

(a) Use of sewer capacity: results for T010



	Low	Moderate	Significant	High
BAU-T010	-7.2%	-1.4%	+6.7%	+1.9%
CAS1-T010	-5.8%	-2.0%	+6.7%	+1.2%
CAS2-T010	-6.1%	-2.2%	+6.1%	+2.2%
CAS3-T010	-0.4%	-6.9%	+5.4%	-0.3%

(b) Use of sewer capacity: results for T020



	Low	Moderate	Significant	High
BAU-T010	-7.2%	-1.4%	+6.7%	+1.9%
CAS1-T010	-5.8%	-2.0%	+6.7%	+1.2%
CAS2-T010	-6.1%	-2.2%	+6.1%	+2.2%
CAS3-T010	-0.4%	-6.9%	+5.4%	-0.3%

(c) Use of sewer capacity: results for T100

Figure 137. Use of sewer capacity: results for CS, BAU and CAS situations.

The strategies simulated are not effective in addressing Lisbon level of hazardousness per se and the strategies for reducing vulnerability are extremely relevant and necessary to face climate change.

Electrical sector

As presented in previous deliverables, Deliverables 2.2 (Russo, 2018a) and 2.3 (Russo, 2019), flooding hazards characterized by using hydraulic modelling, allowed to identify how the electrical sector in Lisbon could be affected. The distribution infrastructure is mostly underground and vulnerability was found to be low even when located in areas where flooding events occur periodically.

As referred in Deliverable 3.4 (Evans, 2019), Lisbon has a high redundancy of service for high and medium voltage, because it is classified as a Quality Zone A. The response times in case of a disruption are more demanding then for other Quality of Service zones and, even for climate change scenarios, the response and recovery of the electrical grid is stable and resilient.

Combining all the historical data gathered with the simulations made in the previous deliverables mentioned above, it was possible to identify which specific assets should have strategies to minimize the risk of failure by implementing the adaptation measures in the relevant assets of electrical infrastructure to face context-specific climate change scenarios.

Globally, the electrical sector was found to have a good level of resilience to flooding given the type and location of the infrastructures as well as the high level of redundancy in the supply to costumers.

Even for the levels of flooding in current and BAU situations, the few exposed components were retrofitted reducing the vulnerability. Any situation resulting in lowering flooding levels is favorable to the operation but not essential for ensuring service continuity. A situation was identified that might have increased exposure from estuary water level increase and strategies proposed allow reducing the vulnerability as well as improve integration in the city.

Mobility and transport sector

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, in the current situation the less important roads in terms of traffic are more exposed to flooding 4^{th} /5^{th} 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 (D2.3).

Using the global results for downtown catchments J and L obtained for CS, BAU and CAS3, in terms of total area flooded, variations are below 10% for all return periods and situations. Variations are considered to be within the error margins of the approach. Since this area is one of the most exposed of the city, the results can be view as an indication of the trend for the remaining areas.

As for flooding in general, the existing situation is not significantly effected by climate change or by the strategies simulated. The other strategies considered are complementary and important to achieve a more relevant reduction of the hazards.

Waste sector

The levels of exposure and vulnerability of the waste sector are quite low and the results indicate a significant residence to flooding of waste collection in Lisbon. For BAU and CAS3 the results show irrelevant differences to current situations in downtown catchments J and L. Since this area is one of the most exposed of the city, the results can be view as an indication of the trend for the remaining areas.

5 General conclusions and lessons learnt

This deliverable provide the description of the modelling activity related to the implementation of several adaptation measures (from specific adaptation strategies planned and implemented by the three RESCCUE research sites) to reduce multi-hazards and risks related to flooding, water quality and drought in the three research sites.

The adaptation scenarios have been compared to Business as Usual and Baseline scenarios se scenarios considered the same climate change drivers provided by WP1 used for the simulations concerning Business as Usual scenario.

Comparative results were expressed though maps, graphs and tables and, in many cases (mainly related to floods and drought), they showed significant reduction of the hazard increments due to climate change. This is, for example, the case of Barcelona, where implementation of SUDS is able to reduce significantly flood hazard exacerbated by climate change in the drainage sector and other important urban services (traffic, electrical system and waste). The complementary implementation of SUDS and Structural measures could reduce drastically flood hazard for return period up to 10 years.

On the contrary, water quality deterioration due to CSOs and turbidity (respectively for Barcelona beaches and Llobregat River) did not show significant variations for BAU. Notwithstanding, SUDS and retention tanks implementation have been also simulated in order to provide useful information regarding water quality improvements respect to Baseline scenario.

For the models related to drought and water resources, adaptation measures and strategies have been defined, but as they will act on vulnerability of the system, their impact reduction will be assessed in Deliverable 3.6.

Globally, the results of the assessment of the strategies for Lisbon are limited by the information and tools available but, in general, the trends are that climate scenarios (BAU) result in a global reduction of performance for all return periods simulated. The strategy CAS1 has potential to compensate slightly the climate change effect. CAS2 has a significant local effect but overall performance is minor. Also CAS3 has a stronger effect locally than globally, but the impact in the global performance is significant. Nevertheless, the values are relatively low. Current situation is not favorable and variations obtained for the scenarios of climate change are likely lower than the errors associated with the model used. Limitations of this very simplified model used as well as lack of data on effective flow capacity must be taken into account when assessing the results.

The strategies simulated are not effective in addressing Lisbon level of hazardousness per se and strategies for reducing vulnerability are extremely relevant and necessary to face climate change.

Regarding the analyzed sectors, for flooding in general, the existing situation is not significantly effected by climate change or by the strategies simulated. Other strategies considered are complementary and important to achieve a more relevant reduction of the risks. For the electric energy supply sector, Lisbon has a high redundancy of service for high and medium voltage, because it is classified as a Quality Zone A and, even for climate change scenarios, the response and recovery of the electrical grid is stable and resilient. For the mobility and transport sector, results indicate a trend of variations below 10% for all return periods and situations. Although these results already provide an indication, specific risk factors need to be analyzed for a more detailed identification of most vulnerable zones and structures. For the waste sector, the levels of exposure are quite low and the results indicate a significant residence to flooding of waste collection in Lisbon. For BAU and CAS3 the results show irrelevant differences to current situations in down town catchments J and L. Since this area is one of the most exposed of the city, the results can be view as an indication of the trend for the remaining areas.

The city of Bristol is exposed to flooding from both pluvial and fluvial combined with tidal flooding events and the effects of these are only going to get worse due to a combination of both climate change and sea level rises. A number of approaches for mitigating the effects of climate change and sea level rises have been investigated by the city of Bristol within the scope of RESCCUE and can be divided into two main categories (impacts reduction via reduction of hazards and impacts reduction via reduction of infrastructure vulnerabilities)

With one of the main predicted drivers of losses for the city being as a result of fluvial and tidal flooding (as outlined in D3.4) one of the identified strategies outlined in this document is the incorporation of flood defenses along the river network. These defenses would in effect avoid the flooding impacts for up to 1 in 200 year flood events (so no simulations have been carried out to assess hazard reduction).

With limited model runs within the central city region the reduction of infrastructure vulnerabilities were investigated in the scope of properties, traffic, and infrastructure within this area. For the traffic modelling side the analysis within this document has highlighted that crucial road sections that connect the South and the North of the city are susceptible to flooding and could have potential implications to traffic flows within the city. Analysis taken from this study will be utilized in an updated traffic model with the subsequent impact assessments discussed in the accompanying follow-on deliverables (D3.5 and D3.6). From the properties and energy sectors side the follow-on deliverables will investigate how localized changes/protection to infrastructures can mitigate impacts.

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