Assessment of compensation measures – Source Control Solutions - in urban drainage systems under climate change

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Abstract:. In this paper a planning analysis of implementing some compensation measures in a small drainage basin in Lisbon, Av. Almirante Reis, is presented. The main objective is to study if the measures that are used can mitigate the increasing stormwater runoff due to climate change. Potential Best Management Practices (BMPs) were first selected and placed in the right areas. Then SUSTAIN (**S**ystem for **U**rban **S**tormwater **T**reatment **A**nd **In**tegration), a decision support system software, was used to get the optimal dimensions for the BMPs. With those, SWMM (**S**torm **W**ater **M**anagement **M**odel) is used to study the impacts that the group of BMPs chosen have in the drainage system. Thus, it is possible to assess whether these measures can compensate or not the decreasing performances of the urban drainage systems due to climate change. Based on the results, BMPs have a positive impact, although it is not enough. Therefore, BMPs should not be seen as the "one and only" solution, but more as one of the solutions among a group of different measures.

Keywords: Climatic changes; Stormwater runoff; BMPs; SUSTAIN; SWMM; Optimal

1   INTRODUCTION

Nowadays, cities are experiencing a significant growth, manly due to the increasing world population and the migratory movements to the urban centres. This urban growth leads to the increase of impervious surfaces and thereafter an increasing of the stormwater runoff, which causes a decreasing in the performance of the drainage systems. Worsening all this, the world is experiencing climatic changes that aggravate even more the drainage systems performances. With this decreasing come serious consequences in terms of flooding, transport of pollutants and contamination of natural systems. Therefore, the need for solutions and adaption to all this changes is nowadays a very important subject, existing under study and experimentation several solutions to this matter.

To mitigate the negative impacts of urbanization, some in recent years have proposed the use of BMPs for stormwater runoff quality and quantity control (Davis, 2005); (Field, et al., 2006); (Jia, Yao et al., 2014). There are presently many BMPs, such as bio-retention cells, porous pavement, green roofs, etc., that could be used at a certain site. Others believe in solutions more i-tech, like the Real Time Control (RTC) of urban sewer systems, which have some applications that were well succeeded (DWA, 2005). Nevertheless, the application of these solutions is residual comparing with the international panorama, which implies that the effectiveness of the application of each one of these solutions may not be the best, due to the lack of experience and results. With that in mind, all these solutions are first modelled in software's that help analysing the results and deciding whether the application will or won't do the effects needed.

In this study, is analysed the effectiveness of using BMPs in a small drainage basin in Lisbon considering climate changes in the precipitation regime and in the river Tagus tide. For that are used two different decision support

systems, SUSTAIN and SWMM, which will help deciding the optimal sizes of the BMPs and if those have the effectiveness needed.

2   APPLICATION OF BMPs AND SUSTAINBLE URBAN WATER MANAGEMENT

The use of BMPs in stormwater management aims to reduce the excessive runoff and the pollutants loads that enter into the drainage system. Source control measures could be non-structural such as alternative layouts of roads and buildings, minimizing imperviousness and maximizing the use of soils and vegetation. On the other hand, structural measures include the construction near the source of the stormwater, of systems such as infiltration and rainwater re-use facilities or green roofs (Barbosa, Fernandes, & David, 2012). In this study, are used four different types of BMPs: Detention Ponds, Green Roofs, Porous Pavement and Infiltration Trenches. All these BMPs have different characteristics and the place in the urban basin where these should be is a complex but essential step for urban runoff control planning (Jia, Yao et al., 2014). Actually, with this type of measure it is possible to rethink some urban areas that need rehabilitation, not just in terms of buildings but socially as well. In fact some of the BMPs used can induct really big differences in the urban area. That's why the application of these solutions must be linked with the urban management and design. The BMPs planning process, often by necessity, need to involve considerations on relevant urban development planning schemes such as urban master planning, land use planning, landscape planning, drainage system planning, water pollution control planning, etc.

With these new solutions to solve the cities drainage problems, a new concept arises – SUWM (Sustainable Urban Water Management) or WSUD (Water Sensitive Urban Design). The main objective of these concepts is allying the rehabilitation of the urban areas and at the same time enhancing the quality and quantity of the stormwater runoff. Thus, cities could treat the stormwater runoff, not as nuisance but more as resource. This new way of managing stormwater involves implementing a range of decentralised solutions and the disconnection of waterways from impervious surfaces, using BMPs and green infrastructures. Thus, SUWM differs from traditional models in its core aims, the type of infrastructures and how the urban water cycle is managed (Marlow, Moglia, Cook, & Beale, 2013). Next, the main objectives that SUWM tend to achieve:

- Stormwater runoff volumes reduction
- Quality control of the stormwater runoff
- Enhance urban design and rehabilitation
- Reuse of stormwater and sewer water

Concluding, the core objective of SUWM is adapting the actual urban water cycle to a more natural water cycle. Below is presented an image that shows this objective and the SUWM concept (Water by Design, 2009).
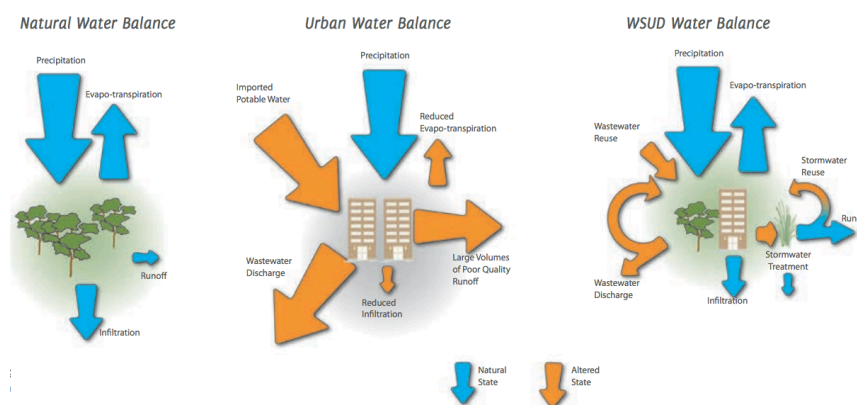

Figure 1 – The Urban Water Cycle showing changes to the Natural Water Cycle with traditional urban development and with SUWM

3 INTRODUCING SUSTAIN AND SWMM – DECISION SUPORT SYSTEMS

Nowadays, with technology advances, all these new solutions and new infrastructures are first modelled and studied with software's, normally addressed as decision support systems. In Urban Stormwater management, especially when using solutions that have lack of expertise, it is very common the use of this kind of software's. In this study, there are used two different decision support systems – SUSTAIN and SWMM, in this chapter is made a little introduction to each one.

3.1 SUSTAIN – System for Urban Stormwater Treatment And Integration

SUSTAIN was developed by the US EPA to evaluate alternative plans for stormwater runoff management in urban and developing areas (US EPA, 2009). It provides a decision-support tool capable of evaluating the optimal location, type, size and cost of BMPs needed to meet water quality and quantity goals. It is built on a platform interface ArcGIS, which provides the user access to the framework components: A BMP sitting tool, a watershed runoff and routing module, a BMP simulation module, a BMP cost analysis module, an optimization module and a post processor (Jia, Yao et al., 2014); (Lee, et al., 2012).

Each module in the framework serves a specific function. The BMP sitting tool uses ArcGIS and user guided rules to determine site suitability. The land simulation module is used to generate runoff time series data to drive the BMP simulation. The conveyance module provides routing capabilities between land segments or BMPs or both. The process-based BMP module provides simulation of management practises by using a combination of hydrological processes. The cost database is organized according to BMP construction components. The optimization module is designed to efficiently search for this combination results in a cost-effectiveness curve (US EPA, 2009). This curve provides valuable information on the minimum costs at various reduction goals, like runoff reduction or pollutant reductions.
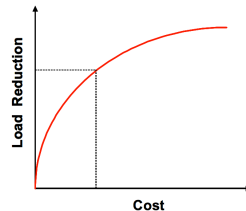

Figure 2 – Sample cost-effectiveness curve

3.2 SWMM – Storm Water Management Model

The Water Supply and Water Resources Division of the US EPA produced SWMM with assistance from the consulting firm CDM, Inc. This software is widely used throughout the world for planning, analysis and design related to storm water runoff, combined sewers, sanitary sewers and other drainage systems in urban areas. SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term simulation of runoff quantity and quality from primarily urban areas. The runoff component operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff trough a system of pipes, channels, storage/treatments devices, pumps and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps (US EPA, 2010). With this tool, it is possible to evaluate the flow in the drainage system and conclude whether it is well designed or it needs adjustments. Actually, SUSTAIN code is based on SWMM's code, that is why modules in each software are almost the same.

4 CASE STUDY – DRAINAGE BASIN OF AV. ALMIRANTE REIS

4.1 Case study site

Av. Almirante Reis was chosen, because it represents a very good example of an urban drainage basin with problems of flash flooding and it has great influence in the occurrence of this phenomenon in the downstream basins and streets. Another aspect that was regarded is the fact that this urban basin has a great potential for urban rehabilitation, so it would be easier to implement some of the BMP's and urban strategic measures like SWUM. In Figure 3, at the image on the right is represented some of Lisbon's sites that are affected by flash flooding; the blue bar represents Av. Almirante Reis, which has an average of ten flash floods per decade. At the image on the left, it is possible to view some buildings from Av. Almirante Reis where it is easy to view the advanced state of degradation and abandonment. Thus, these urban areas have a great potential for rehabilitation and use of SWUM measures.
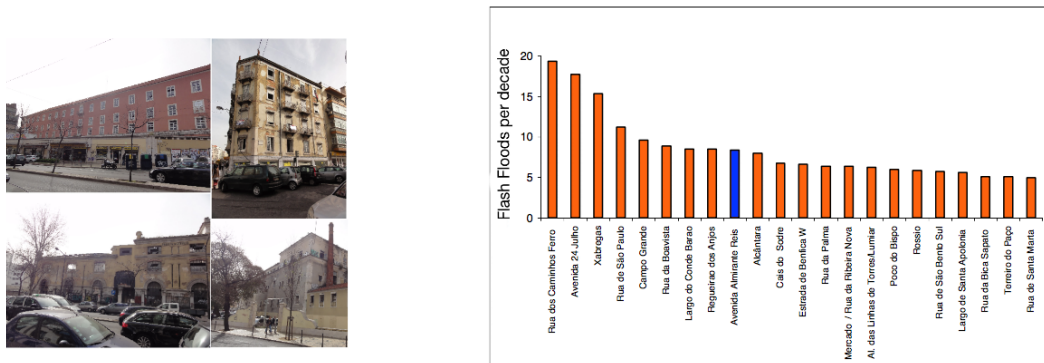

Figure 3 – Main Lisbon sites that are affected by flash floods and some images of Av. Almirante Reis buildings

Av. Almirante Reis is one of the main Lisbon avenues, well in the centre of the city it's a complete urban developed site, with a total of 350 ha, it has a highly rate of impervious areas. The limits of the urban drainage basin that were defined are represented in the Figure 4.

Figure 4 – Delimitation of Av. Almirante Reis urban drainage basin

4.1.1 Soil type

When using source control measures, infiltration is one of the main aspects that is needed to be accounted. Thus, knowing the soil type of your study area, namely the infiltration rate and porosity, is very important for the success of your model. Since SUSTAIN uses the Green-Ampt method to compute the amount of infiltration of rainfall on the pervious land area, where the input parameters can be determined from physical measurements, the Lisbon Geological Cart was consulted so these parameters could be obtained (Câmara Municipal de Lisboa, 2010). With the information gathered from these sources, was possible to define the average characteristics of the soil:

- Suction Head – 198,12 mm

- Saturated Hydraulic Conductivity – 4,5 mm/h

- Initial moisture content – 0,15 (Humid soils); 0,3 (Dry Soils)

4.1.2 Urban occupation

Besides the soil type and the limits of the study area, is very important to define the pervious and impervious areas. In SUSTAIN this definition is mandatory and, in this study were identified four types of different areas, where buildings; streets; parking lots were considered 90% impervious and the other area type is 10% impervious, this last area are mainly, gardened places.

4.1.3 Precipitation event

Since one of the objectives is to study the effectiveness of the application of BMP's in reducing precipitation runoff, another parameter that is essential defining is the precipitation event. In Figure 5, it is represented the precipitation even that was applied in the SUSTAIN and SWMM models. In both models, it was applied this precipitation event aggravated in 20% or without this aggravation. This change was made, because it was considered that with climate change these extreme events would become 20% more intense. For the SUSTAIN model it was analysed three different return periods (T5; T10 and T20)
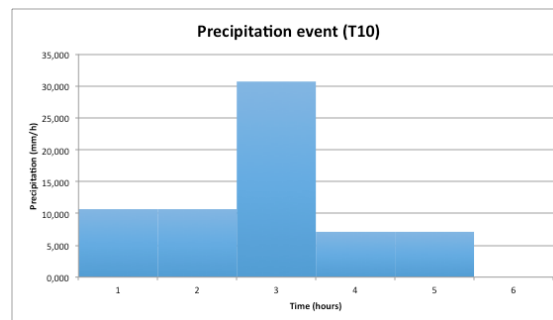

Figure 5 – Precipitation event applied in the SUSTAIN and SWMM models

4.2 SUSTAIN model and results

The main objective of this model is to define the optimum size, of each BMP, that can provide the biggest reduction in runoff. In the end, the best solution will be the one that has more effectiveness for fewer costs.

Since the study area is a complete developed urban area, the areas where the source control measures were applied, were chosen with the idea of requalification of urban spaces. For example, the dry ponds were placed in areas where buildings were completely unoccupied and abandoned.

From the great variety of source control measures that are available, only four different BMP's were used: Dry Ponds; Green Roofs; Infiltration Trenches and Porous Pavement. The BMP layout is illustrated in Figure 6.
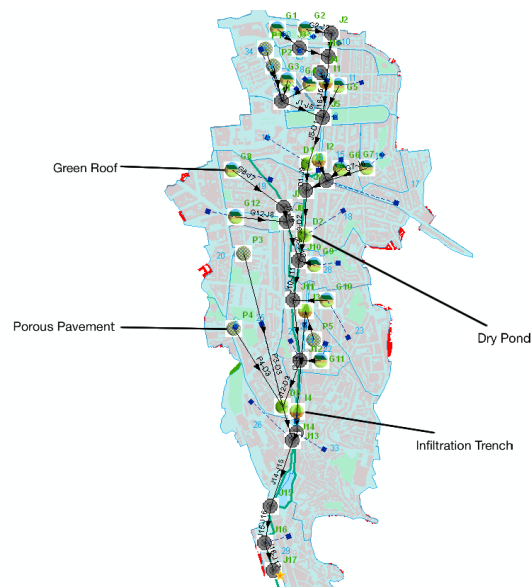
Figure 6 – BMP layout

These BMP's were placed in several places along the drainage basin, with a variable dimension. This means the only thing that was chosen, was the place where the BMP were placed, the optimum dimension is the output from the SUSTAIN model. Dry ponds, infiltration trenches and porous pavement, had their length as variable. Green Roofs had the number of units, where one unit is the size of an average roof, ranging. In Figure 7, are presented the cost-effectiveness curves for different return periods, namely T5, T10 and T20. From this data, it's clear that for precipitation events with more intensity, the effectiveness of the BMP drops.
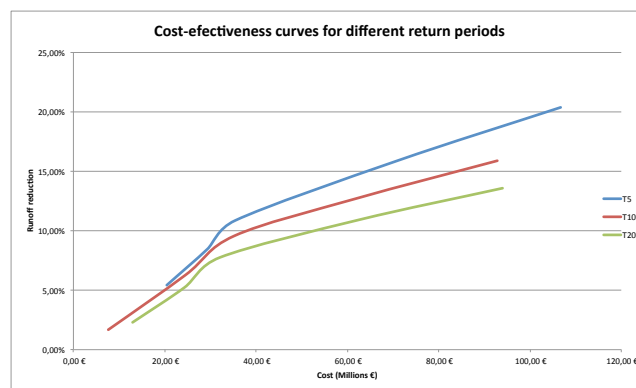

Figure 7 – Comparison of the cost-effectiveness curves for different return periods

When looking to Figure 7, it's possible to conclude that when higher the cost, higher the effectiveness reducing runoff. The best solution is the "knee-of-curve" point.

For a better analysis, were analysed five different solutions, the minimum, the best solution, the maximum and the solutions between these three points. In Table 1, it is possible to see the optimum sizes of each variable parameter that was ranging in each BMP. From these values, it's easy to conclude that when higher the effectiveness of the solution higher the variable sizes of each BMP, which leads to a bigger implantation cost.

Another aspect that is interesting is the fact that the best solution uses mainly Dry Ponds and Infiltration Trenches, which means Green Roofs, are not a very effective source control solution, as these are used mainly in more onerous solutions, like 4 and 5.

6

Table 1 – BMP variables parameters analysis for a T5 precipitation event

| BMP | Variabe Parameters | | | Solution | | | | |
| | Variable dimension | Values Range | | 1 - Min | 2 | 3 - Best sol. | 4 | 5 - Máx |
		Minimum	Maximum					
Dry Pond 1	Length	0	81	6	3	78	78	75
Dry Pond 2	Length	0	93	3	90	90	93	93
Dry Pond 3	Length	0	114	111	111	111	111	114
Green Roof 1	Nº of Units	0	25	5	5	10	10	10
Green Roof 2	Nº of Units	0	20	5	0	0	5	10
Green Roof 3	Nº of Units	0	35	5	15	15	15	25
Green Roof 4	Nº of Units	0	70	10	5	10	40	60
Green Roof 5	Nº of Units	0	240	20	30	20	40	210
Green Roof 6	Nº of Units	0	140	0	0	0	80	140
Green Roof 7	Nº of Units	0	100	0	0	0	60	60
Green Roof 8	Nº of Units	0	240	10	10	20	10	220
Green Roof 9	Nº of Units	0	120	10	20	20	30	90
Green Roof 10	Nº of Units	0	220	10	10	0	190	210
Green Roof 11	Nº of Units	0	90	10	10	10	50	80
Green Roof 12	Nº of Units	0	200	20	20	20	180	180
Porous Pavament 1	Length	0	32	15	30	27	15	9
Porous Pavament 2	Length	0	32	6	6	6	6	6
Porous Pavament 3	Length	0	60	42	12	12	36	30
Porous Pavement 4	Length	0	63	51	51	60	18	24
Porous Pavement 5	Length	0	66	18	42	42	30	48
Infiltration Trench 1	Length	0	381	111	99	183	333	252
Infiltration Trench 2	Length	0	342	60	339	333	276	243
Infiltration Trench 3	Length	0	576	459	195	522	453	75
Infiltration Trench 4	Length	0	639	63	201	51	585	468

4.3 SWMM model and results

The main objective of this model is to input the optimum sizes of the BMP's obtained from SUSTAIN, in a model of the drainage system of the basin Av. Almirante Reis. Thus, it's possible to study the influence that the BMP's have in the drainage system, in terms of flow, volume and flow depth.

The model of the drainage system that was used was developed with the SI-GEA project, where were modelled the unitary drainage system of the Av. Almirante Reis e Av. da Liberdade. This model presents the main conduit, of both drainage systems, and the outfalls to river Tagus, which means these drainage systems are affected by the tide. In this study the tide was considered fixed at 1,9 meters, so we could have an adverse situation without the probability of the precipitation event overlapping the low tide.

In this model were inserted the BMP's from the best solution for a return period of 5 years (seventh column of Table 1), these source control solutions were introduced with the LID-BMP module that SWMM has available. In Table 2, it's presented a summary of the BMP's sizes that were obtained from SUSTAIN and inserted in SWMM. It's important referring that the total cost for this solution is approximately 35,4 millions €.

Table 2 – Summary of the BMP dimensions obtained from SUSTAIN and inserted in SWMM

BMP	Length (m)	Volume (m³)	Total volume (m³)	% of occupied area of the basin
Dry pond 1	78	12776,4		
Dry Pond 2	90	17010	55660,5	0,76%
Dry Pond 3	111	25874,1		
BMP	**Length (m)**	**Area (m²)**	**Total Area (m2)**	**% of occupied area of the basin**
Porous Pavement 1	27	729		
Porous Pavement 2	6	36		
Porous Pavement 3	12	144	6273	0,18%
Porous Pavement 4	60	3600		
Porous Pavement 5	42	1764		
BMP	**Length (m)**	**Area (m²)**	**Total Area (m2)**	**% of occupied area of the basin**
Infiltration Trench 1	183	384,3		
Infiltration Trench 2	333	699,3	2286,9	0,07%
Infiltration Trench 3	522	1096,2		
Infiltration Trench 4	51	107,1		
BMP	**Nº of units**	**Unit area (m²)**	**Total Area (m2)**	**% of occupied area of the basin**
Green Roofs	125	300	37500	1,08%

To analyse the effect of these BMP's in the drainage system, 4 scenarios were made.

- Scenario 1: This scenario represents the city and its drainage system nowadays, without any compensation measures. It also represents the climate that we live nowadays, this means no climatic

changes were inserted, the tide is considered at 1,9 meters and the precipitation event it's not aggravated.

- Scenario 2: This scenario is equal to the first in terms of climate properties, but with source control measures applied.
- Scenario 3: This scenario is represents the future in terms of climate changes and urban development. The precipitation events are aggravated in 20% and the tide is increased in 0,5 meters, finally the BMP's are applied in this scenario, representing the urban development.
- Scenario 4: It's the worst-case scenario, the urban area with no BMP's and all the considered future climate changes.

In this model, two sections of the main conduit were analysed. These sections are both downstream of the last BMP applied, which allows a better analysis of the BMP's results in the drainage system. In Figure 8, these sections are identified in red.
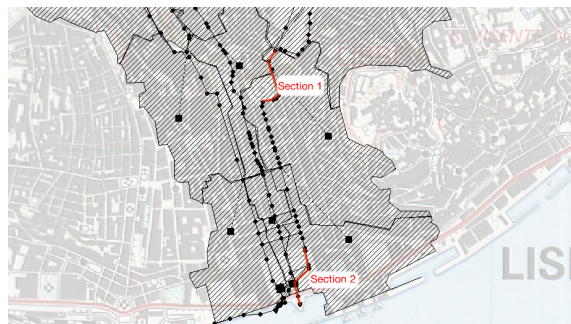

Figure 8 – Identification of both sections that were analysed

4.3.1 Section 1

For this analysis some parameters are taken into account, flow, flow depth and conduit capacity. In Figure 9 are illustrated the profiles for section 1 and a graphic representing the flow along the simulation time. The profiles are representing the worst period of the simulation time.
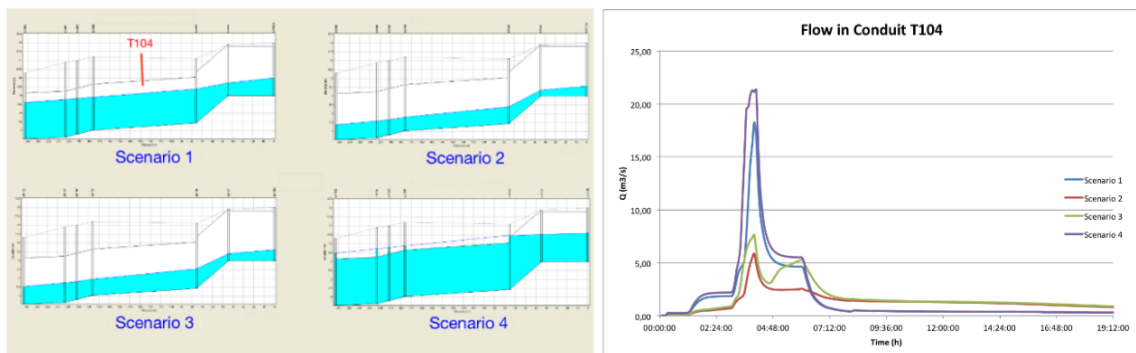

Figure 9 – Illustration of the section 1 flow depth and graphic showing the flow evolution along all the simulation time.

From this data, it's possible to conclude that scenario 2 and 3 allow a significant reduction in terms of maximum flow. This happens mainly because of the dry ponds, which are the BMP with a significant size in the best solution used from SUSTAIN. With these dry ponds, we would expect that the maximum flow would occur later in the simulation time, but that doesn't happen. This happens because the dry ponds are to short for the income of water from the precipitation, so they fill pretty quick and the maximum occurs almost at the same time but with less flow. Actually all the water that is detained is later restored in the system, that is why in both scenario 2 and 3, it's possible to view to maximums. This indicates that the percentage of infiltration is not that high.

4.3.2 Section 2

This section has influence in one of the more problematic areas in terms of flooding in Lisbon, the riverside. Section 2 is more downstream than section 1 and has the influence of the Av. da Liberdade drainage system, which has direct influence in the results. In Figure 10 are illustrated the sections regarding different scenarios and a graphic with the evolution of the flow along the simulation time.
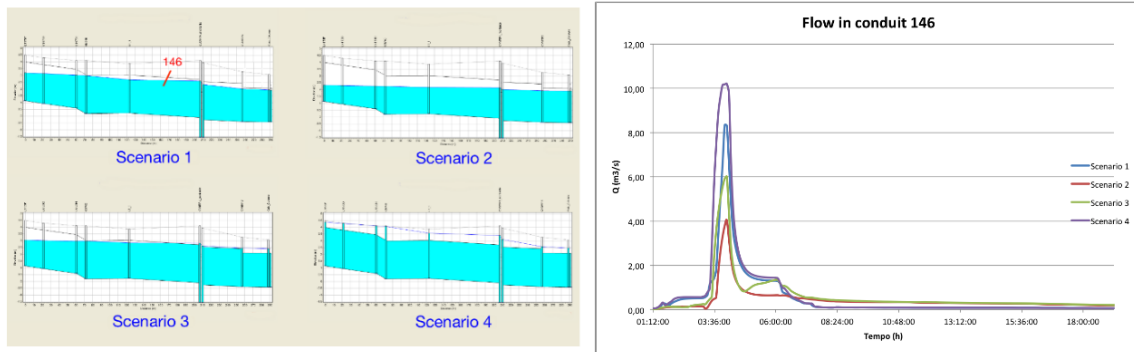

Figure 10 - Illustration of the section 2 flow depth and graphic showing the flow evolution along all the simulation time.

When analysing Figure 10, in scenario 4 the nodes surcharge, which means water rises above the crown of the highest conduit. Although in scenario 3, which has BMP's applied, this situation does not occur. Looking to the graphic, the results are not that different from the ones from Figure 9, but when you look at the same time for image on the left, it's easy to understand that besides the less flow in the scenarios with source control measures, 2 and 3, the capacity of the conduit is always pretty close of the maximum. In Figure 11 is illustrated the evolution of the capacity of the conduit 146 during the simulation time, where is possible to understand that besides the BMP application the conduit capacity is always pretty close of his maximum. Another interesting result is the fact that the evolution of the capacity for scenarios 2 and 3, where BMP are applied, isn't so steep as for scenarios 1 and 4, this is due to the application of dry ponds, where the detained water is later restored more slowly. Again, this proves that the volume differences are mainly due to the detained water and not the infiltration parcel.

This means the tide and other drainage systems, like Av. da Liberdade, influence greatly the effectiveness of the BMP's applied. It's important to understand, that in this study we are only considering some basins, when actually other basins more upstream would influence even more this results.
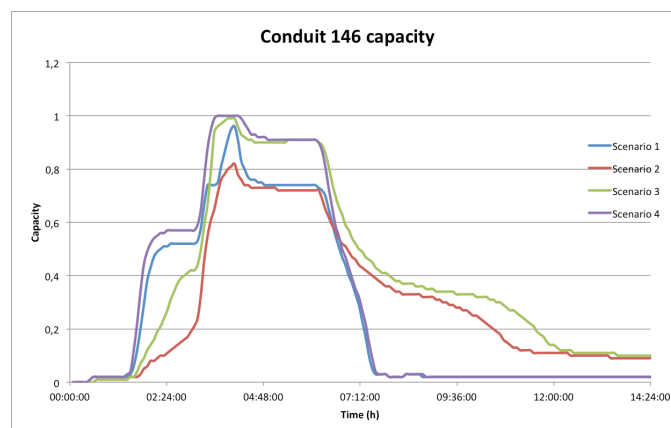

Figure 11 – Capacity of conduit 146 along simulation time

5   CONCLUSIONS

A list of feasible BMP's at appropriate location was planned and the best dimensions for each BMP were obtained regarding cost-effectiveness. Than these BMP's were inserted in a model of the drainage system, in order to study the direct influence that this source control measures had in the drainage system. It's important mentioning that this study regards a futuristic scenario with low probability of being adopted. This is a study from an academic perspective, where we wanted to study the effectiveness of the mass application of source control measures.

The results show that these solutions can lead to the mitigation of the negative impacts that the urban centres are experiencing, but not with the efficiency needed, especially in the riverside. Actually these measures are too expensive for the efficiency presented, which is why source control measures are still seen as additional solutions for the traditional systems. Thus, with all the measures and techniques that we can use to mitigate this problem, the BMP's should not be seen as the *"one and only"* solution, but more as one of the solutions among a group of different measures that are used to adapt the drainage systems in the cities.

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