Assessment of Urban Drainage Improvement Strategies in Climate Change Scenarios

Case Study of Bento Ferreira Basin

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ABSTRACT

The increasing urbanization, the consequent rise in impermeable areas and the effects of climate change lead to an increase not only in the number of urban floods but also in their extent, causing social, environmental and economical damage. The Bento Ferreira basin, in the city of Victória, (capital of Espírito Santo State, Brazil) reflects this problem, as part of a coastal area and provided with a storm water drainage system of low resiliency. In this context, a dynamic model of the drainage system of the Bento Ferreira basin was developed using SWMM software (Storm Water Management Model), and a network simulation in different scenarios was undertaken. Based on the data and improvement proposals specified in the Urban Drainage Master Plan of the Municipality of Vitória (PDDU) and the contribution of climate change, different scenarios of infrastructural intervention were established to tackle the problem of urban floods. The efficiency of each proposal was compared through a cost-benefit analysis.

The best performing solution includes three main components: the construction of four underground storage tanks in strategic locations, the replacement of sewers with limited drainage capacity and the capacity increase of the pumping station installed downstream of the drainage network.

Key-Words: storm water drainage system improvement; urban flood management; resilience; climate change; dynamic simulation model.

1 INTRODUTION

Since the nineteenth century the urban population has been increasing. The rise in impermeable areas, the decrease in the concentration time of the hydrographic basins, the reduction in storm water infiltration and consequent increase of surface runoff results in the aggravation of urban floods as well as the decrease of storm water quality (Zevenbergen et al., 2010). It may also result, particularly in less developed countries, in the spread of epidemics of waterborne diseases (Pinto and Pinheiro, 2006). There is a number of factors that increase the risk associated with flooding, including social pressure on the environment, impacts of climate change, economic and social vulnerabilities and physical vulnerabilities (Tucci, 2007; Ramos, 2013).

Climate change, which is manifested by increasing temperature, precipitation intensity and mean sea level (IPCC, 2014), has an impact on drainage systems and contributes to the aggravation of urban floods. Drainage systems designed based on historical records may not be able to cope with future situations, and adaptation measures must be implemented, which includes the improvement of existing infrastructures to increase urban resilience. This need is also an opportunity to improve current practices, increase awareness and reduce vulnerabilities to floods: a change of conceptions, local action and educational strategies is needed, so that cities can cope with change, becoming more resilient. Dieleman (2013) suggests that one way of enhancing cities' resilience involves teaching and training, applying small-scale innovations and technical reinforcements at the community level, making them more self-reliant and self-resilient.

Recently, several urban flooding problems have been registered in the city of Vitória (capital of the state of Espírito Santo, Brazil). This city combines several negative factors: it is a low-lying coastal city, which limits the drainage pipes slope, and is served by a deficient storm water drainage system, where overflow and consequent urban flooding is recurrent, causing social and economic damage to the urban population. Based on the Urban Drainage Master plan (PDDU) developed by the Municipality of Vitória (PMV, 2008), the aim is to analyze the drainage system of the Bento Ferreira basin in the city of Vitória and to develop structural measures to reduce the frequency and impacts of urban floods. Currently, the Bento Ferreira basin (with an area of 2.97 km^2), has a separate drainage system and a pumping station downstream of the network, that pumps the water directly to the sea.

The studied solutions were established for different precipitation and sea water level scenarios, that take into consideration current and future situations, considering climate change, through the simulation of the drainage system in the SWMM software (*Storm Water Management Model*). The efficiency of each proposal was compared through a cost-benefit analysis.

2 CLIMATE CHANGE

Climate change is linked to any substantial change in the parameters that quantify climate (such as temperature or precipitation) that lasts for an extended period of time (decades or centuries). Climate change has occurred since the beginning of Earth's history due to natural causes. However, human activities have been accelerating this process, contributing, significantly and quickly, to global change.

The greenhouse effect has been increasing since the industrial revolution in the eighteenth century, mainly due to the combustion of fossil fuels to generate electricity and the mobility of vehicles. This combustion promotes the emission of greenhouse gases into the atmosphere where they can remain for extended periods of time, from decades to thousands of years. The main greenhouse gases are carbon dioxide, methane, nitrous oxide and fluorinated gases and have a cumulative effect on the atmosphere, meaning they accumulate energy in the lower parts of the atmosphere for extended periods of time. The consequences are clear: temperature, precipitation and sea level rise, glaciers melt, and the life cycles of animals and plants change (EPA, 2016).

The effects of climate change on precipitation are reflected, mostly, in the increase in precipitation intensity: heavy rainfall events will become more and more frequent, while the return period is decreasing. According to IPCC (2014) an increase of up to 20% in precipitation intensity is forecast until the end of the 21st century. The PBMC (2014) - Brazilian Panel on Climate Change - estimates an increase between 5 and 10% in the first half of this century and between 25% and 30% by the end of the century. It is estimated that the average sea water level has grown at an average rate of 3.2 mm/year between 1993 and 2010, compared to an average rate of 2 mm/year between 1970 and 2010. According to the IPCC (2014) the bias is that in the worst-case scenario, where the level of emissions is highest, sea level will increase by 0.74 m by the end of the 21st century and, at worst, increase by 6.63 m to 2500. However, the Delta Commission (Dutch) predicts an increase between 0.2 and 0.4 m by 2050 and, in the worst-case scenario, 1.3 m by the end of the 21st century (Stead, 2013).

The combined effect of increasing precipitation intensity and sea level rise contributes to the risk of flooding: coastal cities must cope with a significant increase in seawater level which can lead to catastrophic events. At the same time, saline intrusions in urban drainage systems can affect wastewater treatment and jeopardize its reuse (Proença de Oliveira et al., 2015).

3 CASE STUDY

3.1 Study area characterization

The Bento Ferreira basin, with an area of 2.97 km^2, an average slope of 0.0135 m/m and an average concentration time of 1h, is part of the municipality of Vitória (capital of the state of Espírito Santo, Brazil), which is a coastal city in southeast region of Brazil (Figure 1). The city of Vitória has an extensive history of urban flooding, such as during December 2013, when the largest extreme precipitation event of the last 50 years in the city took place (INMET, 2017) with a magnitude of about 713.9 mm (monthly) and a daily maximum of 120 mm. The Bento Ferreira basin is one of the zones affected by most floods, according to Figure 2.

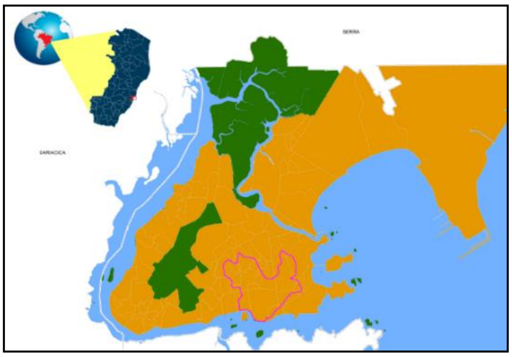

Figure 1 - Location of the case study area (PMV, 2017).

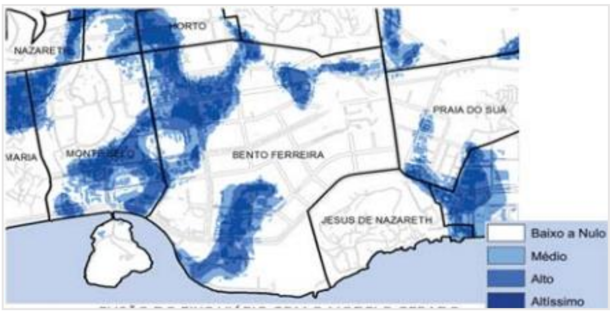

Figure 2 – Map with flood regions in the Bento Ferreira Basin, during the heavy rainfall event of 2014 (Coelho, 2015).

The alarming situation in Vitória, and particularly in the Bento Ferreira basin, is a problem with two fronts, since urban floods affect public roads and different services in the city (such as hospitals and schools) over an extended period of time, even for rainfall events of relatively small durations. The drainage network has gaps in its design, which can hinder the correct transport of storm water downstream, increasing the length of time the water remains in the city's streets and, consequently, its impact on society. The basin in question is equipped with a separate branched storm water network (Figure 3) and routes the runoff to 2 pumping stations (in the same location) with a total capacity of 12.2 m^3/s (5 pumps of 1 m^3/s + 4 pumps of 1.8 m^3/s) which pumps the water into the sea (Discharge_1, in Figure 3,on the left). The network has also an extra branch, which routes the runoff directly into the sea, without the support of a pumping station (Discharge_2, in Figure 3, on the left). This network includes pipes with small slopes and manholes with invert elevation below the zero-reference point.

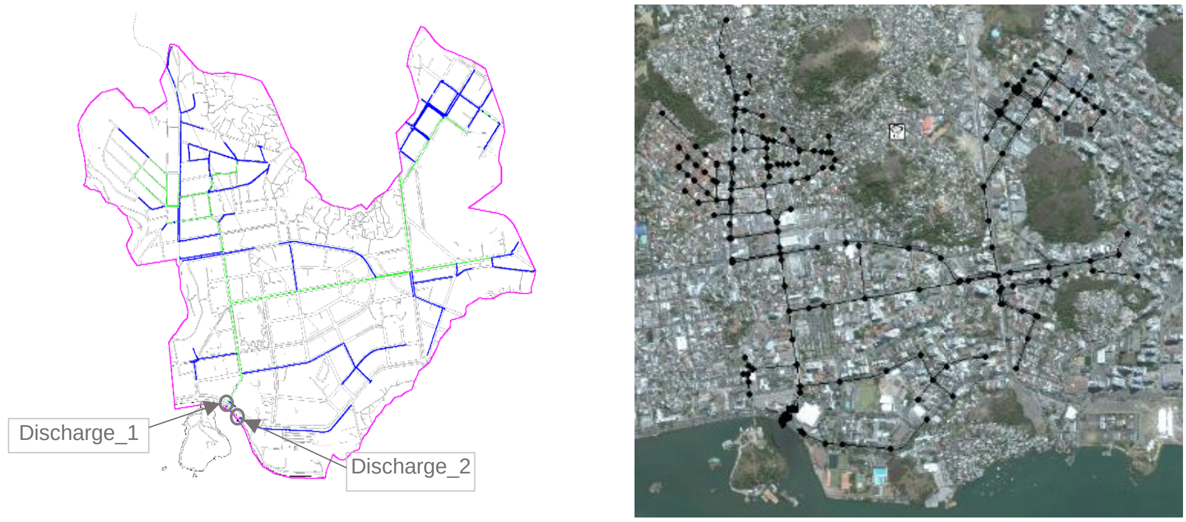

Figure 3 – Drainage network of the case study: Bento Ferreira basin.

3.2 Adopted methodology

The drainage network was implemented in SWMM software (Figure 3, on the right side) and simulated through different scenarios of precipitation and sea level variation, with different approaches regarding structural interventions. (the alternative solutions to improve the drainage system were based on the proposals established in the PDDU (PMV, 2008)).

The model developed and implemented in SWMM was simulated based on the flood hydrograph and the mean sea level established by the PDDU, for two return periods: T = 10 and T = 25 years (the last one assumed as the current scenario). In addition, future scenarios of climate change, with a 10 and 20% increase in precipitation intensity (calculated over the return period of 25 years scenario) and 0.4 to 0.8 meters in average sea level (IPCC, 2014), were considered. The analyzed solutions incorporate three main types of intervention: the construction of underground storage tanks, the expansion/improvement of the drainage system and the increase of the pumping station capacity. Different combinations of these interventions were established and a cost-benefit analysis was undertaken to clarify the feasibility of each proposed intervention.

3.3 Design storm and sea water level

The method proposed both in PDDU (PMV, 2008) and in the drainage manual of the city of Vitória (PMV, 2014) was used to calculate the precipitation intensity, according to equation (1):

$$I = \frac{973.47T^{0.19}}{(t_d + 20)^{0.77}} \quad (1)$$

where:

- I – Precipitation intensity (mm/h)
- T – Return Period (years)
- t_d – Rainfall event duration (minutes)

For the temporal distribution of precipitation, the triangular hydrograph method and a duration of 60 minutes were adopted, according to the established by the PDDU (PMV, 2008).

The tide tables published by the Brazilian Navy (DHN, 2017) were consulted for the calculation of the mean sea water level and a 24-hour recorded period with values above average was selected. These values were also converted to the reference system used in the drainage network layout (IBGE, 2017). In addition, two climate change scenarios were defined, an optimistic one and a pessimistic one. The calculated values for the different scenarios presented are shown in the following Table 1 and in the graphs of Figure 4 (precipitation) and Figure 5 (sea level).

Table 1 – Precipitation and sea water level for different scenarios.

	Increase in precipitation (%)	Precipitation intensity (mm/h)	Increase in sea level (m)	Maximum sea level (m)
T=10 years	-	51.6	-	0.56
Current scenario (T=25 years)	-	61.5	-	0.52
Optimistic scenario	10	67.6	0.4	0.92
Pessimistic scenario	20	73.7	0.8	1.32

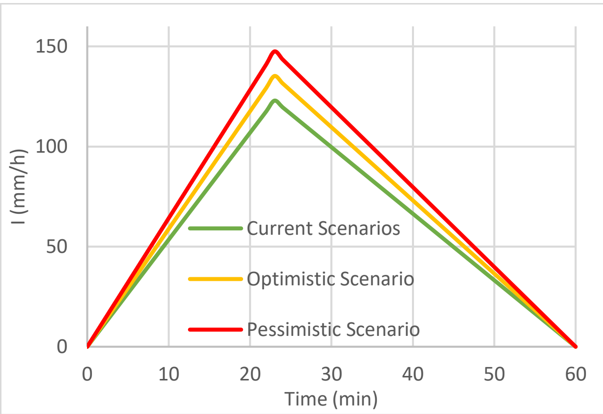

Figure 4 – Flood hydrograph for different scenarios.

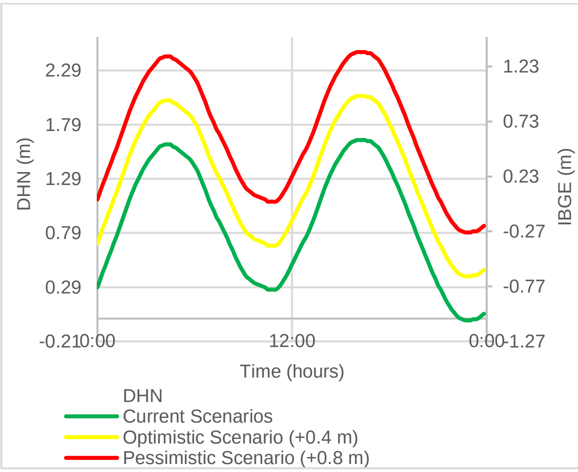

Figure 5 – Sea level for different scenarios.

3.4 Results

The simulation of the model for the current scenario (T = 25 years) led to the conclusion that the main problems of the network are:

a) Several nodes (manholes) with flooding throughout the network (Figure 6, on the left side).

b) The flow rate in the sewers exceeds its flow capacity (Figure 6, on the right side).

c) water concentration in lowland areas, generating great heights of water in the public highway, through long periods of time.

Flooding occurs in 85 nodes, with a total flood volume of 64.61x10^3 m^3. The height of water accumulated in the lowland areas can be calculated by dividing the overflow volume by the total flooded area (estimated at 125x10^3 m^2), as per equation (2):

$$h_{water} = \frac{V_{overflow}}{A_{flooded}} = \frac{64.61}{125 \times 10^3} \times 10^2 \approx 50\ cm \quad (2)$$

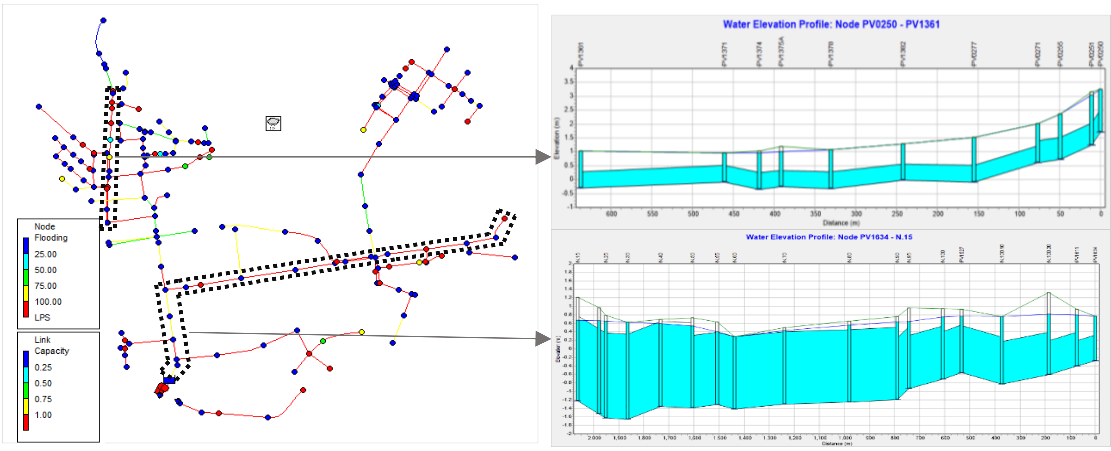

Figure 6 - Performance of the current system through the current scenario (return period of T = 25 years.)

Based on part of the proposals described in the PDDU, four alternative solutions were created, each with different components: Solution 1 represents the current situation of the system (1-A), with a small increase in pumping capacity (1-B). Solution 2 proposes the construction of four underground storage tanks (2-A), with an additional increment of the pumping capacity (2-B). Solution 3 represents the two main interventions proposed by the PDDU (3-A and 3-B), which includes both the construction of storage tanks and the installation of complementary sewers, as well as an increment in the pumping capacity. Solution 4 suggests a combination of the different interventions that proved to be most favorable and necessary, as well as the substitution of pipes that exhibit critical behavior throughout separate stages (4.1, 4.2, 4.3, 4.4 and 4.5). The results regarding solution 3 are not specified in this article, due to the low benefits associated with it, when compared to other solutions.

i. Pumping Station Capacity Increase

The increase of the pumping capacity in the different solutions (Solutions 1,2 3 and 4) was done according to the PDDU, which suggests a total capacity increase of 12.2 m^3/s to 18 m^3/s, replacing 5 pumps with nominal capacity of 1 m^3/s with 6 pumps with nominal capacity of 1.8 m^3/s.

i. Underground Storage Tanks

The four storage tanks (which are part of the interventions included in Solutions 2, 3 and 4) were to be installed in public spaces, according to the PDDU, which made possible the measurement of the respective cross sections areas (admitted as rectangular, located in Figure 7). In order to calculate the volume of each storage tank it was necessary to determine their depth, which was estimated through an iterative process during different simulations of the system to store excess volumes in the network.

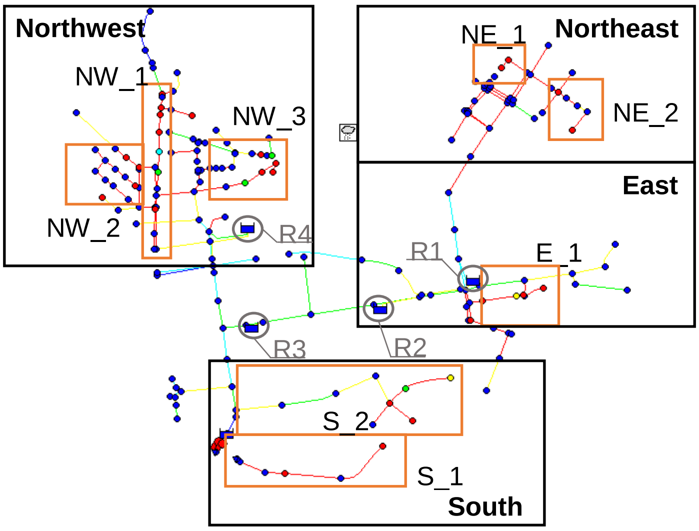

Figure 7 – Interventions in the drainage system. Storage tanks locations and identification of problematic areas.

The occupied areas are 3000 m^2 for the storage tanks R1, R3 and R4 and 1700 m^2 for the storage tank R2. The corresponding volumes are between 11050 m^3 (storage tank R2) and 19500 m^3 (storage tank R1). Different rectangular bypass pipes have been installed to route excess flows to the storage tanks and return circular pipes have been installed to empty some of the storage volume by gravity whenever possible. Also, pumping stations were installed in order to restore the storage volume that does not have the ability to flow by gravity. Each one will have a capacity of 1 m^3/s (except the one regarding storage tank R2, with a capacity of 0.5 m^3/s) in order to empty all the storage tanks in about 4 hours.

i. SEWERS SUBSTITUTION

In Solution 4, in addition to the construction of underground storage tanks, different sewers substitution was also analyzed in four critical areas: Northwest, South, Southeast and East, as shown in Figure 7, in order to propose a construction phasing and assess the benefits associated with each area of intervention. The following stages were considered: stage 4.1 includes interventions in the Northwest area; stage 4.2 adds the southern area to the previous stage; stage 4.3 adds the East area to the previous stage; stage 4.4 adds to the Northwest area and stage 4.5 adds the increase in the pumping station capacity.

The design criteria of the new pipes were to ensure that there was no extravasation of nodes, to minimize excavations and negative slopes, to guarantee an acceptable flow velocity (less than 5 m/s and, if possible, greater than 0.6 m/s) and to ensure that the downstream flow rate of the interventions is less than the upstream flow rate, when possible. The proposed interventions include the replacement of circular pipes (with 600 mm diameter) by other circular pipes (800 mm or 1000 mm) and/or rectangular pipes, with a variable base between 1 and 3.5 meters, and a variable height between 0.9 and 1.5 meters. In total they cover about 3.5 km of network.

i. RESULT ANALYSIS

In Table 2 is shown, for each solution established and for the optimistic scenario of climate change (corresponding to a 10% increase in precipitation and 0.4 m in sea level), the number of flooding nodes, the respective duration of flooding, the total volume overflow and the respective height of water in the flood prone areas. The current scenario (corresponding to a return period of T = 25 years) causes lower magnitude damage in all solutions. With the installation of all the interventions (Solution 4.5), there is a total overflow volume of 3.0x103 m^3 and a corresponding water height of 2.4 cm. On the other hand, the pessimistic scenario of climate change causes a total overflow volume of 7.46x10^3 m^3 and a corresponding water height of 5.96 cm, for the same solution (4.5).

Table 2 - Functioning comparison of the different solutions for the optimistic climate change scenario (increase of 10% in precipitation and 0.4 m in sea level).

	Number of nodes with flooding for each solution and for the optimistic climate change scenario								
Flooding intervals (min)	1-A	1-B	2-A	2-B	4.1	4.2	4.3	4.4	4.5
[0:00, 00:15]	44	40	24	24	14	18	19	20	11
[00:15, 00:30]	18	18	16	16	9	7	7	6	6
[00:30, 00:45]	18	18	13	13	8	6	4	3	4
[00:45, 01:00]	8	8	5	5	3	1	1	1	0
Total number of nodes with flooding	88	84	58	58	34	32	31	30	21
Total overflow volume (x 10^3 m^3)	79.45	65.59	33.74	33.66	19.10	6.15	5.60	5.46	4.47
Water height in lowland areas (cm)	63.46	52.39	26.95	26.89	15.26	4.91	4.48	4.36	3.57

It is worth noting the progressive improvements associated with each intervention. The construction of the storage tanks leads to a significant improvement in the system. Compared to the behavior of the existing network, this solution presents an approximate reduction of the overflow volume and water height in flood prone areas to half. The different replacement pipes provide a progressive improvement, but with a lower magnitude, compared to the storage tanks. The installation of all the proposed interventions (i.e., Solution 4.5) causes a decrease in the overflow volume to 4.7x10^3 m^3 and in the water height in the flood prone areas to 3.57 cm, a negligible value in the public road.

A cost analysis of these solutions was conducted, based on the prices considered in the Lisbon Drainage Master Plan (Hydra e Engidro, 2015). The unit prices of the storage tanks were estimated at 300 €/m^3. These costs include all constructive aspects and equipment, such as remote management and control valves. Different unit costs were defined for the sewers, ranging from 320 €/m (rectangular sewers of 1.0x0.9 [mxm]) and 1200 €/m (circular pipes of 1000 mm diameter). For the increase in the pumping station capacity, a total cost of approximately 1.3 M€ was assumed. The total cost of the storage tanks can be estimated at 20 M€ and the cost of the sewers at 3.13 M€ which together with the increase of the capacity of the pumping station, makes up a total cost of 24.5 M €. The cost was also compared with the prices practiced in Brazil, based on the PDDU (PMV, 2008) and other projects records. The estimated values based on the Lisbon Drainage Master Plan are relatively higher than the Brazilian prices, which may be due to the difference in labor prices or the lack of consideration for equipment associated with the construction of the storage tanks, among others. Figure 8 shows a relation between the cost of each intervention and the benefits associated with it (represented with the water height in flood prone areas) with focus on the best performing interventions.

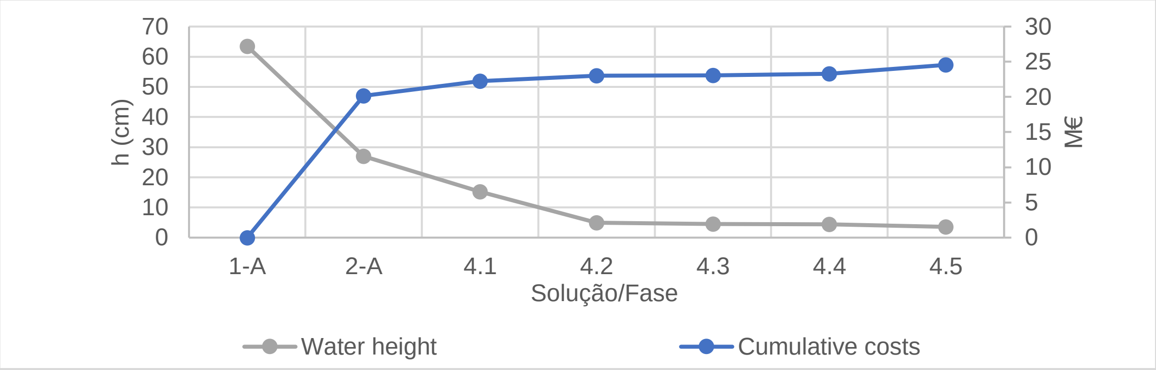

Figure 8 – Cost-benefit analysis for the optimistic climate change scenario.

It can be concluded, that the construction of storage tanks is the priority need for the Bento Ferreira basin (2-A), although it is the solution which requires the higher investment. The remaining interventions are beneficial, but on a smaller scale and with an additional cost of 5M€, as it can be seen in the progress of the graph in Figure 8. It is worth highlighting the advantages of stage 4.1, that is, the interventions in the area Northwest, since it has relatively low costs compared with the associated benefits. It is therefore proposed, by means of accessible funding, the following order of construction: first the construction of the storage tanks (Solution 2-A), followed by the improvement of the North-West area (stage 4.1) and finally the remaining solutions corresponding to stages 4.2, 4.3, 4.4 and 4.5.

4 FINAL CONSIDERATIONS

This paper aimed to analyze the magnitude of urban floods associated with climate change in the Bento Ferreira basin, in the city of Vitória (state capital of Espírito Santo, Brazil). For this purpose, a dynamic model was developed in SWMM software to simulate the drainage system of the Bento Ferreira basin in different scenarios with and without consideration for climate change. The system is undersized for both current design values (return period of T = 25 years and sea level based on historical records) and scenarios with increases based on climate change (10% and 20% increase in precipitation and 0.4 to 0.8 meters at sea level). Consequently, different structural interventions are proposed. After the implementation and simulation of these interventions, and through a cost-benefit analysis, it can be concluded that the priority interventions are the construction of the four storage tanks, followed by the replacement of sewers (the Northwest area being the priority area) and finally, the increase of the pumping station capacity.

In addition to the structural solutions, there are other attitudes that can be adopted to deal with this problem, based on the resilient cities concept. These include: development of risk maps; education and awareness of society; the monitoring, transparency and communication with the inhabitants, especially those who live in risk areas and creation of evacuation and contingency plans. This requires a complementary approach which addresses the situation from a demographic and social perspective.

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