water

MDPI

Article

Climate Change Impacts and Flood Control Measures for Highly Developed Urban Watersheds

Carla Voltarelli Franco da Silva [1], Andre Schardong [2,*], Joaquin Ignacio Bonnecarrère Garcia [1] and Cristiano de Pádua Milagres Oliveira [1]

1 Department of Hydraulic and Environmental Engineering, University of Sao Paulo, Sao Paulo 05508-900, Brazil; carla.voltarelli@usp.br (C.V.F.d.S.); joaquinbonne@usp.br (J.I.B.G.); cpmoliveira@usp.br (C.d.P.M.O.)

2 Department of Civil and Environmental Engineering, Western University, London, ON N6A 3K7, Canada

* Correspondence: aschardo@uwo.ca; Tel.: +1-226-272-0040

Received: 11 May 2018; Accepted: 20 June 2018; Published: 23 June 2018

check for updates

Abstract: Flooding and overflow are recurring problems in several Brazilian cities, which usually face disorderly development. The causes vary, and include increased impervious surface areas, deficiency/inefficiency of drainage structures and lack of maintenance, siltation of rivers, channel obstructions, and climatic factors. In this paper, we present an analysis of mitigation measures to minimize flooding in a watershed located in the core of the city of São Paulo, the biggest city with the highest gross domestic product (GDP) in Brazil. Observed rainfall records and existing intensity duration frequency (IDF) curves for the region are used to obtain design storms. To account for climate change, the equidistance quantile matching method for updating IDF curves under climate change, a well-known procedure, was applied to the existing historical data. Several different global climate models (GCMs) and one regional model were applied to obtain and update rainfall design storms. The GCMs and future scenarios used were from Intergovernmental Panel on Climate Change—IPCC Assessment Report 5 (AR5) and two future projections—representative concentration pathway (RCP) 4.5 and 8.5. Spatially distributed reservoirs combined with low-impact development (LID) measures were used to evaluate different design storm scenarios combined with return periods of 25 and 100 years as well as the updated IDF under climate change for RCP 4.5 and RCP 8.5. Results show that the proposed changes to the drainage system can help reduce the risk and damage of flooding. The climate change scenarios, however, impose a significant threat and need immediate attention from city planners and stakeholders.

Keywords: urban flood; hydrologic and hydraulic modeling; retention structures

1. Introduction

The Anhangabau watershed lies in the central portion of the city of São Paulo, Brazil, emptying into the Tamanduatei River, which arises from other municipalities in the metropolitan region. São Paulo was established in a flat area between the Tamanduatei and Anhangabau rivers. For over 300 years, life in São Paulo existed only because of these two rivers: The Anhangabau was smaller, with clean drinking water, while the larger Tamanduatei served for navigation. With consequent urban development, the rivers have become obstacles to the city's growth. The construction of the Chá Viaduct in 1892 in the valley of the Anhangabau River was the first achievement to overcome the barriers that the rivers imposed on city expansion. In the 1920s, the Anhangabau park was created on the river, which was already rectified and buried. In the late 1930s, a city road plan was proposed, aiming to use valley bottoms for the construction of new avenues. This plan started a practice that was established as a model in city structuring, where water routes gave way to cars. Floods in the Anhangabau watershed have become a critical and chronic problem, an issue that has been studied for decades. The region is highly urbanized with important road connections. During periods of heavy rain, portions of this road network become compromised due to floods at the bus terminals, main streets, and tunnels, completely disrupting the flow of vehicles and creating a chaotic situation for the population, as well as losses to the national economy [1]. It is believed that climate change plays an important role in frequent flooding in the region. Many authors [2,3] have forecast an increase of extreme events, based on global and regional projections for future climate scenarios.

This phenomenon is confirmed by many studies [4–7] on climate change and its effects on cities and urban centers around the world, using a variety of techniques and methodologies. It heavily influences flood risk in cities, especially highly urbanized and populated centers. The accuracy of future engineering projects may be affected by changes in storm patterns due to climate change [8]. The review presented in [9] emphasizes that public spaces are among the areas most vulnerable to climatic hazards and questions the specific social potential of adapting vulnerable public spaces, considering the need for alternatives to current flood management practices. Climate models, global or regional, are known to be uncertain regarding long-term projections. Therefore, it is crucial to access a range of climate change scenarios to address the uncertainty within GCMs and regional climate models [2].

Additionally, some authors [10–12] have highlighted the need to analyze the effects of future climate changes on urban drainage systems as part of the analysis scenarios. Another study [13] showed the relevance of adverse impacts of future climate changes by considering scenarios with adaptation measures, according to projects to reduce future flood volumes and climate change mitigation measures. According to the author of [14], urban floods have a significant impact on people, the economy, and the environment. These impacts can be exacerbated by climatic and socioeconomic changes. Resilience thinking has become an important way for urban planners and decision-makers to manage flood risks. As a result, every flood impact assessment is incomplete, and analysts should be aware of the biases and omissions that exist in any methodology [14].

In the current study, the results are presented in form of hazards and risk maps. Risk maps are presented [13] as useful tools to estimate the risk of future flood scenarios, which may represent a starting point for establishing contingency plans to mitigate flood risk.

In the presented study, some alternatives are considered to attenuate the effect of flooding, aggravated by the climatic change effect. These alternatives to improve drainage performance of urban systems may include mechanisms that provide for retention as a distributed reservoir and low-impact development (LID). The objective of LID is to reduce runoff and mimic the predevelopment hydrology of a site, minimizing disturbed areas and impervious covers, and then infiltrating, filtering, storing, evaporating, and stopping rainwater flow near its source [15,16]. According to the author of [17], the performance of LID projects can and will be affected by unfavorable climatic conditions, such as wet conditions before large or consecutive rains. Thus, the analysis of reservoirs and LID under these critical conditions will improve the project selection process with respect to adaptation to climate change. Results found by the author of [18] for 10-, 25-, 50-, and 100-year events of 24 hours' duration indicate that LID practices probably have benefits for storm flow control, even during large storms.

The objective of this study is to evaluate a new alternative applied to the region of the case study, based on modern concepts of water resource management such as distributed reservoirs and LID control measures and their performance under changing climatic conditions. A complex modeling network employing PCSWMM [19] is elaborated, to represent all road and drainage systems and their interconnections. With the assessed model, the alternative that was intended to mitigate the flooding problem in the lower valley is evaluated with different designed rainfall storm scenarios.

2. Materials and Methods

The Anhangabau watershed is located in the central region of São Paulo, with an approximate population of 80,000 inhabitants, covering an area of approximately 5.4 km^2. The Anhangabau River is formed by the confluence of three streams: Saracura, Itororo, and Bixiga. The basin's macro-drainage system consists of a set of buried galleries that drain the waters of these tributaries under the main roads that cross the basin, joining other under the Praca da Bandeira. It is worth mentioning that the Moringuinho River is in fact a tunnel as part of the drainage system, which was built under an initiative to reduce flooding in the Anhangabau valley region, diverting part of the Itororo River flow directly to the Tamanduatei River. Figure 1 illustrates the basin location in the city of São Paulo, its main hydrographic, and main points of interest.

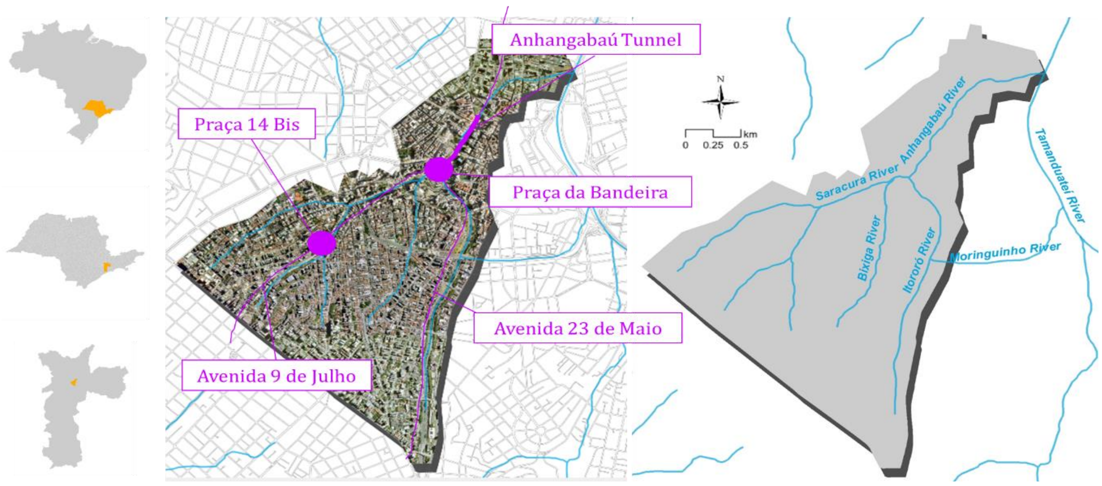

Figure 1. Location, main rivers, and points of interest at the Anhangabau watershed.

The floods that occur on public roads and private areas of the Anhangabau watershed are extremely frequent. Data provided by the Center of Emergency Management of Climate of the City of São Paulo show that the occurrence of floods between January and April 2018 was once in the Anhangabau tunnel, seven times in Praca da Bandeira, twice in Avenida 23 de Maio, twice in Praca 14 Bis, and once in Avenida 9 de Julho.

The previously mentioned studies (from 2004 and 2006) proposed for the region are briefly presented as follows:

- **Alternative proposed in 2004:** This alternative consists of a reservoir under Praca da Bandeira (46,000 m^3), a reservoir under Praca 14-Bis (36,000 m^3), galleries interconnecting them, overland flow catchment, and partial reinforcement of existing galleries under Avenida 9 de Julho. The reservoir under Praca da Bandeira was designed with two wells and an adjacent circular format. According to the project, only those structures will protect the Anhangabau tunnels against events of about five-year recurrence. In the second phase of construction, a reservoir under Praca 14-Bis was proposed, consisting of two adjacent polygonal wells and replacement or repair of existing galleries along Avenida 9 de Julho, ensuring protection against originally planned 25-year return events.
- **Alternative proposed in 2006:** The main objective for this alternative was to cause as little interference with the transportation system of the region as possible, projected for a 100-year recurrence. The project was proposed based on derivation of the full flow of the catchment area upstream of Praca da Bandeira (estimated at 137.6 m^3/s) in a tunnel about 1.6 km long and 6.2 m in diameter, in addition to providing a system of galleries at Avenida 9 de Julho using nondestructive methods. Similarly, considering the position of the bypass tunnel upstream of Praca da Bandeira, it would not be necessary to extend the galleries along Avenida 9 de Julho to the existing galleries in Anhangabau valley.

For the current study, we modified another alternative proposed in 2011 that uses tunnels and large transverse dimension galleries to be deployed along the basin valley bottoms, in order to soften discharge generated by heavy rainfall. In our analysis, we introduced the concept of retention distributed over the basin, projecting conduits to be spread in small watersheds (less than 50 ha catchment area).

The interventions proposed for the basin consist of replacing existing drainage network pipes with flatter conduits that have larger sections and outlet control facilities, which would constitute a network of distributed reservoirs. These reservoirs are substantially longer than wide, following street paths and the existing network. Tunnels and galleries distributed along public roads and watercourses were designed, seeking to follow, wherever possible, existing minor drainage networks. In addition to promoting flood control over wider areas, this proposal allows construction impact on the most critical regions of the basin to be reduced. Among the planned measures are substitution and/or reinforcement of existing galleries under Avenida 9 de Julho and Avenida 23 de Maio and other main streets. Flow control over various segments of distributed reservoirs should be possible through discharge control elements. For this purpose, fixed orifices were chosen, complemented by weirs that would drain all the excess volume after filling the segment.

Implementation of the distributed storage system will result in a network extension of 11 kilometers, as presented in Figure 2a, which shows the area of the Anhangabau watershed with the layout of the proposed distributed storage system.

Low-impact development (LID) controls were selected considering the space limitations for retention and runoff infiltration structures. Surface slopes, existing vegetation coverage, and public areas were first classified to identify the most suitable locations to place such controls. Permeable pavements are proposed for pedestrian streets within low-slope subcatchments near the Anhangabau valley, rain gardens are suggested at public green areas, and infiltration trenches are suitable for public parks or plazas. Figure 2b depicts where land use meets the criteria adopted for implementing LID controls.

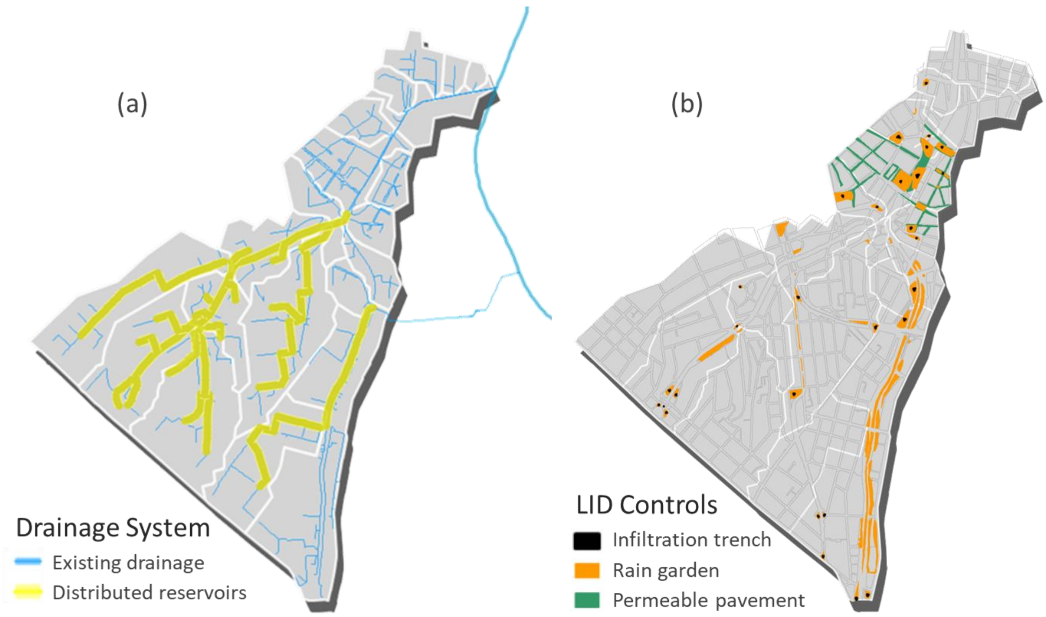

Figure 2. Proposed intervention measures: (**a**) distributed reservoirs under city roads; (**b**) low-impact development (LID) controls.

2.1. Structuring and Implementation of the Model

The hydraulic efficiency of the alternatives was evaluated using a computational model for hydrological and hydraulic simulations with identical criteria for all alternatives. The model used was the Storm Water Management Model (SWMM), available from the US Environmental Protection Agency (EPA) [20–22], with the PCSWMM interface developed by Computational Hydraulics International [19].

The EPA model has been updated to assess the hydrological performance of various types of LIDs and supports a function that compares simulation results before and after the installation of LID practices. Several studies have used SWMM applying LIDs [23–28].

The study used the Soil Conservation Service (SCS) curve number (CN) method to calculate the infiltration process, and the dynamic wave method to route flows through the drainage system, which is the most complex and accurate model to simulate the occurrence of conduit overflow through manholes. The proposed solutions were evaluated with the application data outputs, provided in the form of hydrographs or velocity and water depth diagrams, corresponding to overland flows. The modeling is related to the physical characteristics of the watershed in order to represent the dynamics of natural phenomena:

- Simulated rainfall represents observed rainfall events or defined design storms and future projected storms modified due to climate change.
- Subcatchments contain the information necessary to represent the processes of infiltration, interception, and surface runoff.
- Buildings act as obstructions to overland flow.
- Pathways temporarily store and drain runoff according to surface information.
- Drainage grates and curb inlets make the connection between surface flow and subsurface drainage network, which can also work under pressure.

For the assessment of surface water depths generated above the underground gallery network, a representation was created on two levels connected by orifices, known as a dual network. The first level is composed of the surface drainage system, which is represented by the ground surface directly above the galleries, i.e., roads and terrain that receive subcatchment runoff inputs. These inputs enter the second level of modeling according to established rules for the interconnection between these levels. The second level is made of hydraulically underground galleries that, once surcharged, can cause the energy grade line to surpass the ground level, generating floods just above the ground, again respecting the rules of communication between the underground network and routes. Figure 3 illustrates the processes described.

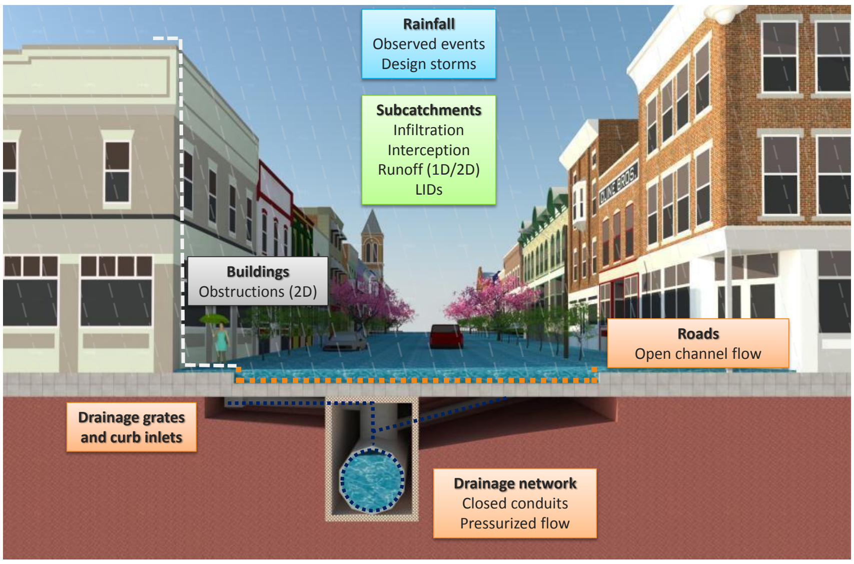

Figure 3. Schematic modeling representation for PCSWWM.

The city of São Paulo's official cartography standard, the Digital City Map (MDC), was applied to represent the relief, geometric conformation, land occupancy, buildings, sidewalks, public roads and streets, and other areas (e.g., plazas, gardens, and green areas), as well as the subcatchment of natural drainage elements that influence inflow to the macro-drainage system. The MDC is the result of an effort by the city to standardize its database, developed through modern aerial survey techniques with flights performed in 2004, which generated maps on the scale of 1/1000 and contour lines of 1 m vertical intervals.

To ensure more homogeneous subcatchment contributions, the basin was divided into small catchment areas, discharging into superficial nodes from the hydraulic network, following the discretization of the road network. The surface road system (excluding tunnels) is represented by 2196 nodes, and the basin was divided into an equal number of subcatchments.

The geometric characteristics of the main basin macro-drainage system, consisting of underground galleries and all the singularities and manholes, were obtained from previous studies and projects developed for the city. Data from surveys performed in the 1990s were used, supplemented by surveys conducted by recent gallery inspections. The minor drainage system is formed by a set of storm sewers with diameters up to 1.2 m, whose slopes were estimated following surface slopes, considering a minimum cover of 1 m where measured data was not available. The connection between underground and surface networks is made through orifices that obey rules proportional to the characteristics of facilities, such as drainage grates and curb inlets, which were acquired from municipal records and supplemented by field surveys. These representative facilities not only are consistent with the inflow entry process in storm sewers, but also meet in case of overflow from the underground network to the road system channels. The rules of entry and exit of such facilities have been defined for each type of drainage grate or curb inlet, with estimated parameters such as height, width, and runoff coefficient, based on the studies of [29].

The existing network features were introduced into the model first, followed by those of the designed systems. The basic hydraulic model represents, altogether, 110 km of roads, 50 km of drainage networks, and 2802 joint facilities as curb inlets and drainage grates. Figure 4 shows the distribution of model elements in the region.

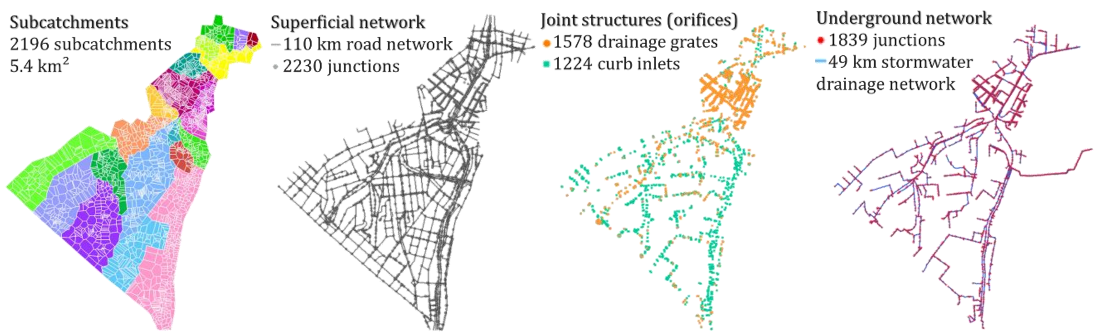

Figure 4. Modeling network for PCSWWM model and current drainage system.

One should also consider the influence of the Tamanduatei River flow regime, which could worsen the conditions of Anhangabau watershed discharges during events of critical intense rainfall in the Tamanduatei watershed. On the road system outfalls spread around the basin, free boundary conditions were chosen, while the outfalls at the Tamanduatei River have fixed levels, depending on the simulated return period, estimated from older hydraulic studies of the river.

Through model calibration analysis and field surveys, it was possible to verify that the drainage system efficiency is significantly reduced in this basin due to the accumulation of waste in the galleries, trash clogging drainage grate curb inlets, and conduits in poor condition. Given this interpretation, the initial model was structured with some additional energy losses in the ducts and hydraulic elements. The results showed that, with the introduction of energy losses, it was then possible to better represent observed events [19]. These exaggerated loss coefficients, however, were not maintained in the simulation of the following scenarios presented in this paper, which should not affect their comparison, since they were all analyzed under the same conditions.

Additionally, the drainage grates and curb inlets had their capacities expanded along the proposed distributed reservoirs. Furthermore, the dimensions of the orifices and weirs that control the flow between tunnel reaches were optimized, aiming to maximize the distributed storage system and minimize the effects of flooding on roads and tunnels.

In order to represent proposed LID controls, the resulting simulation parameters were estimated through a combination of porous permeable pavements, rain gardens (represented in PCSWMM as the bio-retention cell type), and infiltration trenches. Areas for possible implementation of LID controls were evaluated considering no overlapping of LID types, with the adoption of infiltration trenches and rain gardens prevailing. Hydrologic and hydraulic modeling of the Anhangabau watershed was done considering its current situation and the scenario with implementation of the distributed reservoirs. Each scenario corresponds to a combination of drainage system, adoption of LID controls, and rainfall time series.

2.2. Rainfall and Climate Change Scenarios

The design storms applied were characterized through intensity-duration-frequency (IDF) relations, which assign average precipitation intensity at a given duration and probability of occurrence, usually expressed as a period that is the inverse of frequency. These relations are obtained by a series of intense rainfall data, sufficiently long and representative. The IDF curves used for our studies are inferred from the station IAG/USP E3-035 (with coordinates 23°39′ S, 46°38′ W) fitting a Gumbel probability function [30,31] and using the method of moments to estimate its parameters [30–32]. This station has a long observation record, from 1933 to 1997 (65 years), as described by the author of [33]. The alternating block method is applied to the temporal distribution of rainfall obtained using IDF relations, adopting a two-hour critical duration. This distribution is not related to physical phenomena, but is an empirical method that characterizes a critical condition. Return periods selected correspond to 25 and 100 years.

For the climate change scenarios, the IDF_CC tool [34–36] was used to create the updated IDF curves. The tool allows users to generate IDF curve information based on observed data as well as future climate projections using projected precipitation series from the GCMs. Multiple future greenhouse gas concentration scenarios (representative concentration pathways, RCPs) are available in the tool for 24 GCMs simulating various climate conditions that affect local rainfall data [34,35].

The IDF_CC tool adopts a quantile-matching (EQM) precipitation downscaling method to update IDF curves, described in [34]. It is based on (i) similarity of the distribution of changes between the projected period and the baseline period (temporal downscaling), and (ii) spatial downscaling of the annual maximum precipitation (AMP) derived from the GCM data and observed sub-daily data. The quantile-mapping functions are directly applied to AMP to establish the statistical relationships between the AMPs of GCM-generated precipitation data and sub-daily observed data. The relationship built between the GCM baseline and the station's historical observations is assumed to remain the same in the projected future IDFs. The IDF_CC tool offers multiple GCM choices for updating IDF curves for future climate scenarios. The user can select all models (ensemble option) or an individual GCM and a projection period. The gridded GCM data for both baseline period and projection period are spatially interpolated to station coordinates using the inverse square distance weighting method. Table 1 presents a summary of the IDF curves obtained for the current case study and the projected changes for the future scenarios in regard to the historically observed IDF curves. The projected changes in precipitation range from 18% to 53% increase.

The scenarios included in our analysis correspond to five distinct IDF curves for the historical period, using observation records, for two design storms' 25- and 100-year return periods: Two RCPs (4.5 and 8.5) for the climate model (CanESM2) and the ensemble of 24 climate models; and two drainage system arrangements, current and proposed retention interventions with the LID strategy were observed.

Table 1. IDF Curves for the observed data (historical) and for projected scenarios, RCP (representative concentration pathway) 4.5 and 8.5 for the ensemble (ENS) of all 24 models and for the CanESM2 model.

RP (Years)	Historical	ENS RCP 4.5		ENS RCP 8.5		CanESM2 RCP 4.5		CanESM2 RCP 8.5	
	Total (mm)	Total (mm)	Change (%)	Total (mm)	Change (%)	Total (mm)	Change (%)	Total (mm)	Change (%)
2	46.8	60.8	29.9	55.5	18.6	63.5	35.6	71.9	53.6
5	62.1	81.4	31.0	77.9	25.4	84.3	35.7	95.4	53.6
10	72.3	94.7	31.0	93.8	29.8	98.0	35.6	111.0	53.6
25	85.1	109.4	28.7	113.0	32.8	115.5	35.7	130.5	53.5
50	94.6	120.4	27.3	126.9	34.2	128.4	35.7	144.3	52.6
100	104.0	131.2	26.2	140.4	35.0	141.1	35.6	151.8	45.9

2.3. Hazard Indices

Stormwater projects and floodplain management have to be concerned about people's safety in flooded urban areas. Several studies have been published over the last years following intensive research on the risk of analysis in flood areas, [37–40].

In [38], human size characteristics (H.M) are used as an independent variable in defining general flood flow safety guidelines, but this is not considered practical given the wide range of such characteristics within the population. To define safety limits that are applicable for all persons, hazard regimes are defined. Low hazard regimes are indicated where D.V (flow depth and velocity) < 0.4 m^{2}s^{-1} for children (H.M = 25 to 50 mkg) and D.V < 0.6 m^{2}s^{-1} for adults (H.M > 50 mkg). A moderate hazard zone, which is dangerous for some adults and all children, is defined as D.V = 0.6 to 0.8 m^{2}s^{-1}. Flow values in the range of D.V = 0.8 to 1.2 m^{2}s^{-1} represent a zone of significant risk (dangerous to most), and a flow value of 1.2 appears to be the upper limit on tolerable flow for all experiments and across all human sizes [38].

The comparison of the various scenarios was done with the assessment of water depth on roads and sidewalks and the hazard index. The methodology aims to contrast hazard areas at distinct levels of hydraulic risk, considering the depth of water on the roads and runoff velocity. The classification of various levels of hazard is shown in Figure 5, which was adapted from the work of [40] and compared with hazard bands as defined in [38].

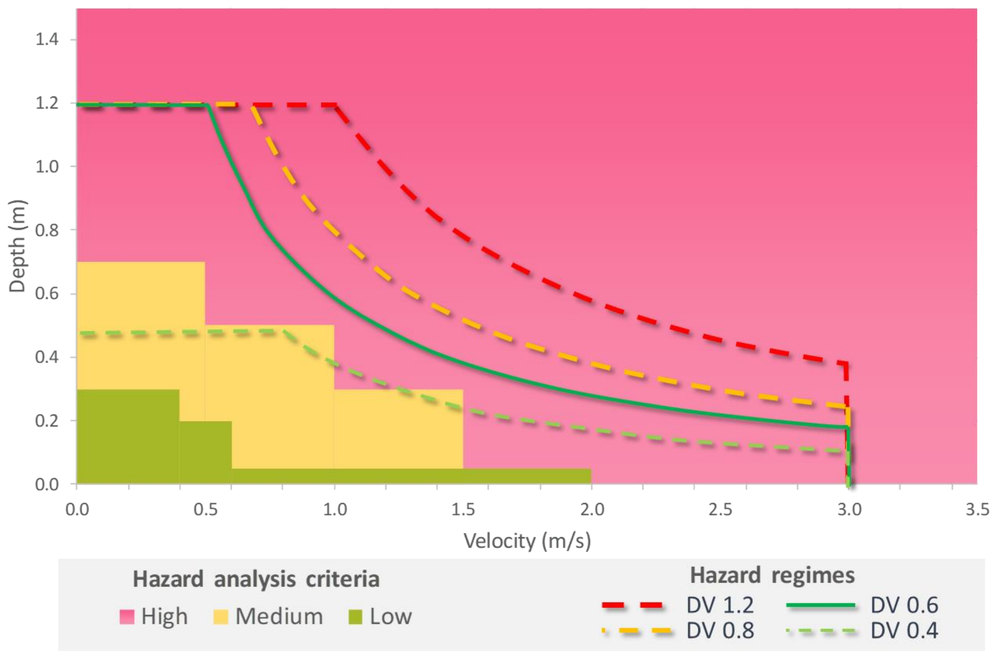

Figure 5. Hazard analysis criteria used in this paper modified from [39] and hazard regimes presented in [37].

2.4. Impact on Buildings

From surface flood levels, a flood risk analysis of buildings was carried out, quantifying the risks as low, medium, or high. In total, 10,730 buildings were evaluated. This analysis was conducted from a flood elevation assigned to the building, originating from the digital terrain model (DTM), compared to the water head in the road segment closest to the building. This analysis tool is part of the differentials of the PCSWMM interface. Low risk was classified as flood level restricted to street level, average risk was situations where the water depth reaches 15 cm on the sidewalk, and high risk was locations where the water depth reaches up to 15 cm on the sidewalk.

3. Results and Discussion

The results are presented in terms of water surface levels, hazard indices, and impact on buildings for the current drainage system, the proposed retention system, LID controls, and climate change scenarios.

3.1. Surface Water Levels

The water levels are presented in five different colors in Figure 6, and the roads are colored according to these classes. Figure 6 shows the results for 25-year return period storms under different climate change scenarios for the current drainage system and proposed distributed storage system with the same storm design scenarios. Both drainage system scenarios clearly showed an increase in water levels for the projected future scenarios, with a maximum of 26% of roads affected by 0.5 m of water or more for the CanESM2 model and RCP 8.5, increasing from 13% for the historic storm to the current drainage. With the distributed storage system, the extent of roads with water level higher them 0.5 m ranged from 3% to 12% for all design storm scenarios. For all scenarios, the lower regions of the watershed in the valley bottoms along Avenida 9 de Julho, Praca da Bandeira, and Anhangabau tunnel had higher concentrated water levels, as shown in Figure 6. However, when we compare the simulation of the current drainage system and the distributed reservoirs, we can see that the extension of roads with surface water levels of less than 0.15 m is significantly larger in the latter.

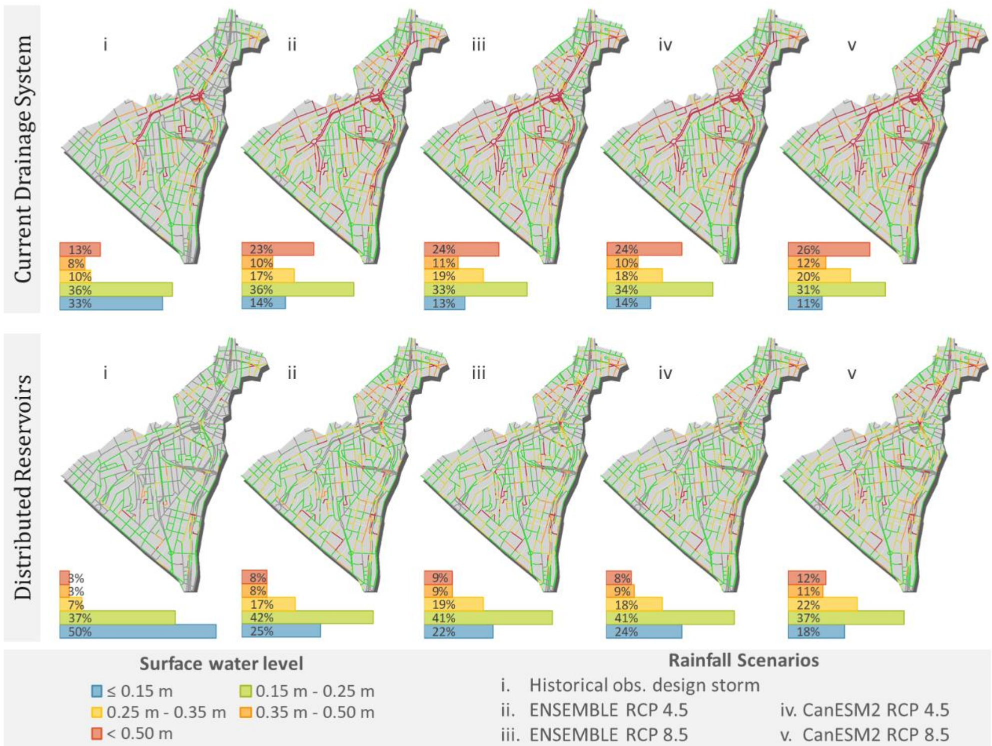

Figure 6. Surface water level results, 25-year return period storm.

For both scenarios, the current drainage system and the distributed reservoirs considered LID control measures for the analyses. With the interventions using the proposed distributed storage system, the improvement to the watershed with reductions in water depth is evident, comparing the current and projected interventions on the drainage system in Figure 7 for each of the design storms, 25- and 100-year return, including the climate change projections.

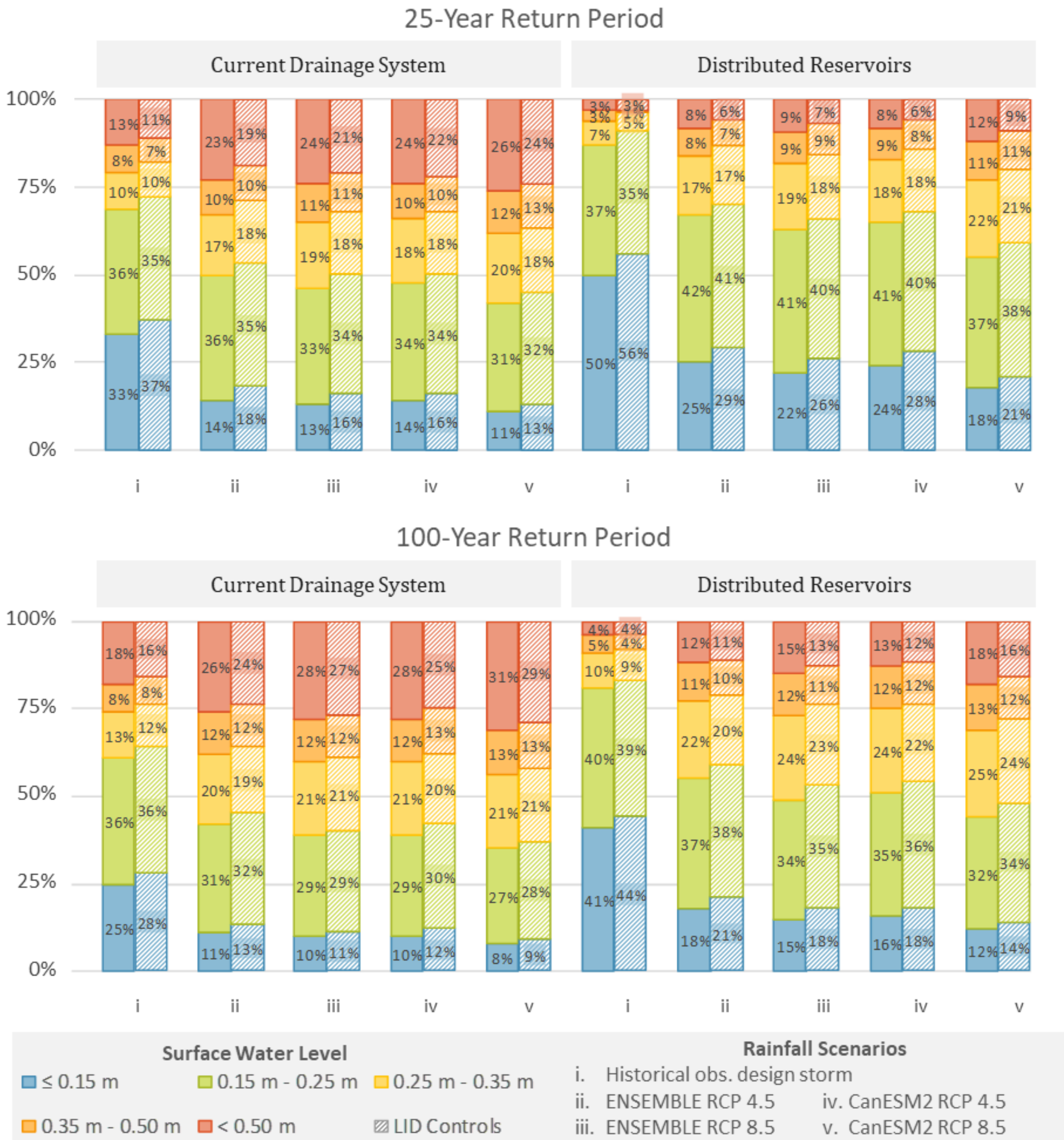

Figure 7. Surface water level result comparison of 25- and 100-year return periods.

As expected, the results obtained for 100-year return period storms show a reduced extent of roads with low surface water levels and an increase in the extent of roads with depth greater than 0.5 m.

What can be noticed, however, is that with the extreme climate change scenarios, especially RCP 8.5, the water depths are comparable to the scenario with the current drainage system and the historical storm. This raises concern and should alert the city's decision-makers that immediate action is needed.

3.2. Hazard Indices

The results of the hazard analyses for selected historical and climate change design storm scenarios are presented in Figure 8 for the current drainage system and the drainage system incorporating the distributed storage strategy. From both maps, what is clearly noticeable is that the climate change scenarios increase the percentage of high-risk levels. For the current drainage system, the high-hazard index increases from 18% to 35% for the CanESM2 RCP 8.5 model. The lowest increase is for the Ensemble approach and RCP 4.5, where the high-risk level reaches 30% (Figure 8). With the implementation of the distributed reservoirs, the high-hazard index increases from 6% to 21% for the CanESM2 RCP 8.5 model.

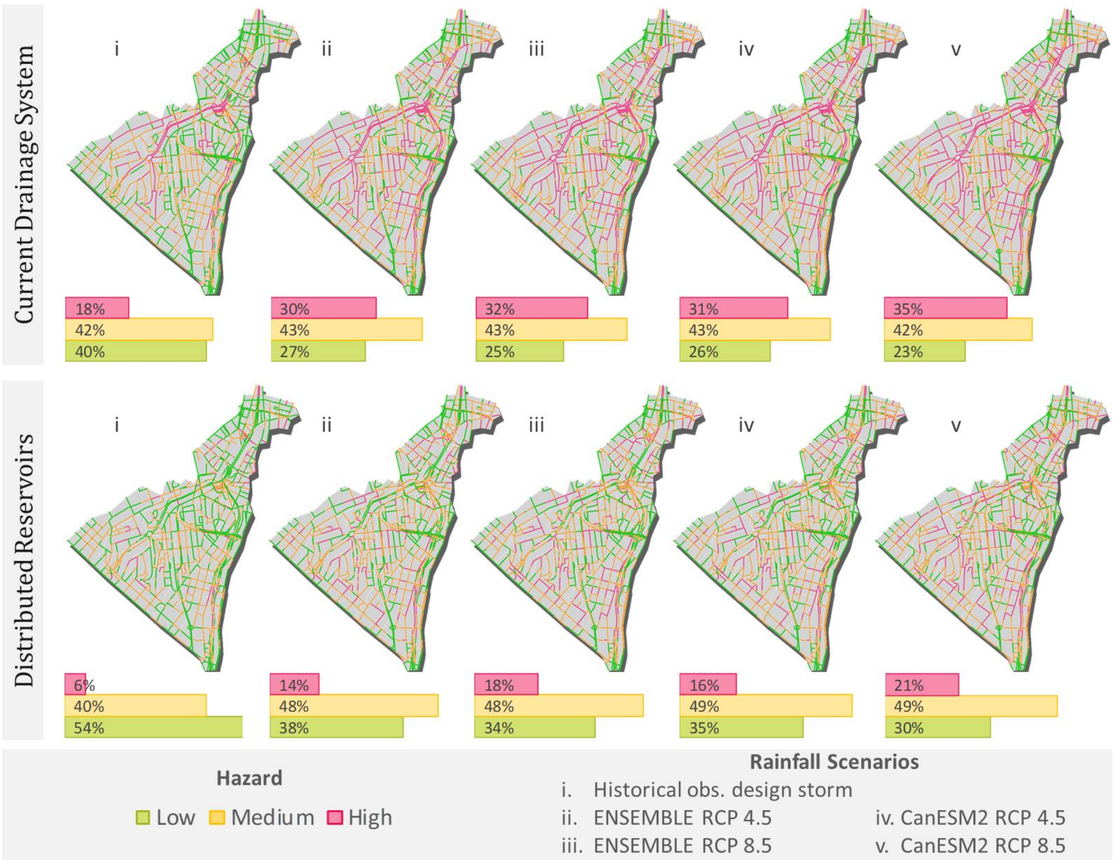

Figure 8. Hazard analysis results, 25-year return period.

Summaries of the results of the hazard analysis for both drainage systems are presented for comparison purposes in Figure 9, considering the 25-year and 100-year return periods. From the results it is clear that the distributed storage system is effective in reducing the watershed areas exposed to high risk in all design storm scenarios. For the historical observed storm, the areas subject to high levels of hazard are reduced to 6% with the proposed drainage system from 18% with the current system for the 25-year return period. For the 100-year return period, these values range between 23% and 9%. For all rain scenarios and both drainage systems, the behavior of the LIDs was evaluated, and a small improvement of the hazard is seen.

Figure 9. Hazard analysis result comparison of 25- and 100-year return periods.

An interesting analysis of the hazard increment for climate change scenarios based on historical observed design storms can be seen in Figure 10. In this figure, the displacements between levels of hazard from low to medium and high, when more severe rain scenarios are analyzed, can be seen.

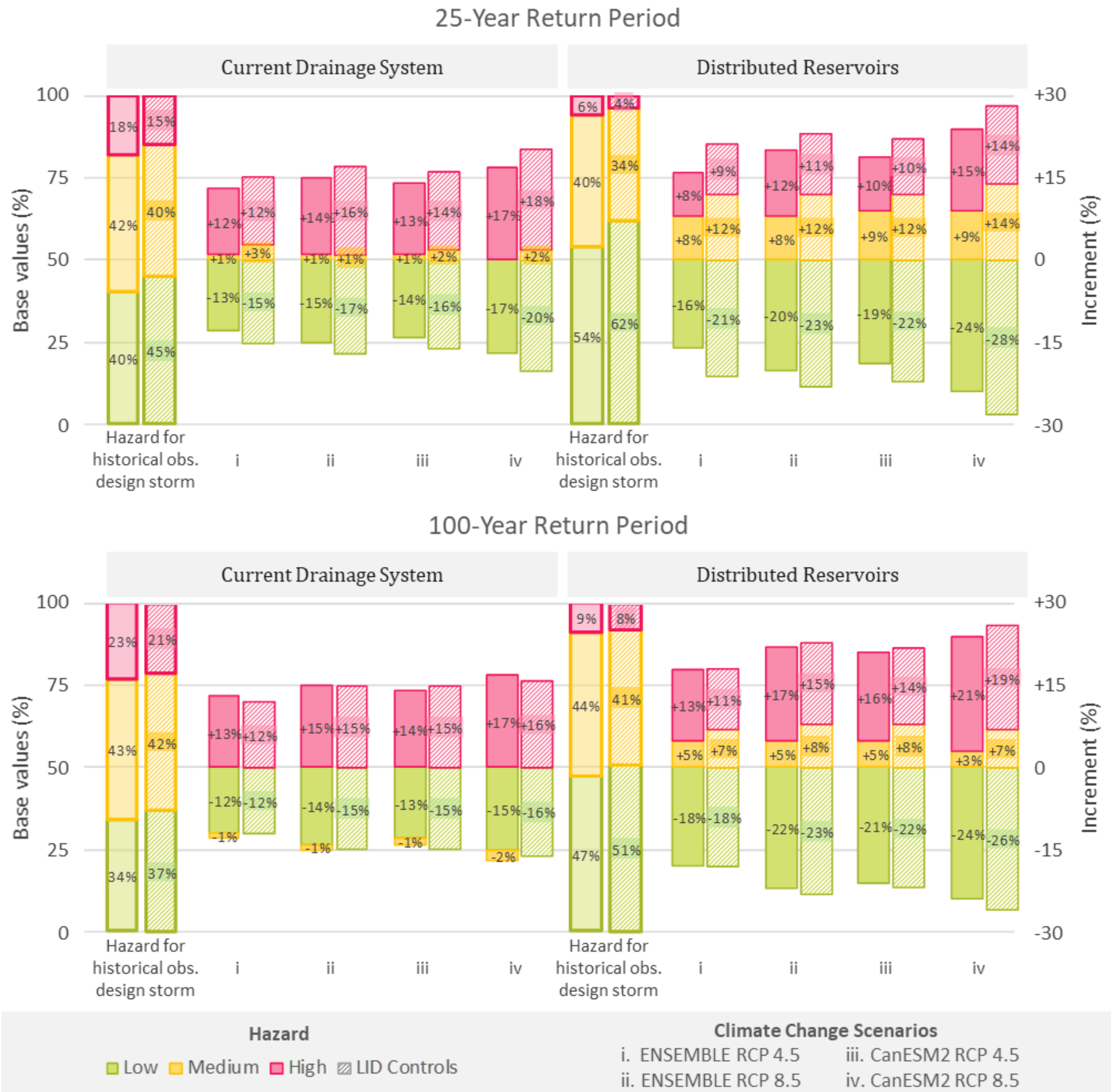

Figure 10. Hazard increment for climate change scenarios based on historical observed design storms.

3.3. Impact on Buildings

Assessing the flood risk of buildings is crucial to help decision-makers and managers understand the level of risk for buildings and structures. Figure 11 presents a flood risk analysis of buildings for 25-year return period storms. For the current drainage system, the high-risk level increased from 13% with the observed design storm to 27% with the ensemble of all models and RCP 8.5, and to 25% for the CanESM2 model and RCP 8.5. With the proposed distributed storage strategy, the values of high-level risk of buildings for CanESM2 RCP 8.5 increased from 6% to 22%, and to 14% for ensemble RCP 8.5.

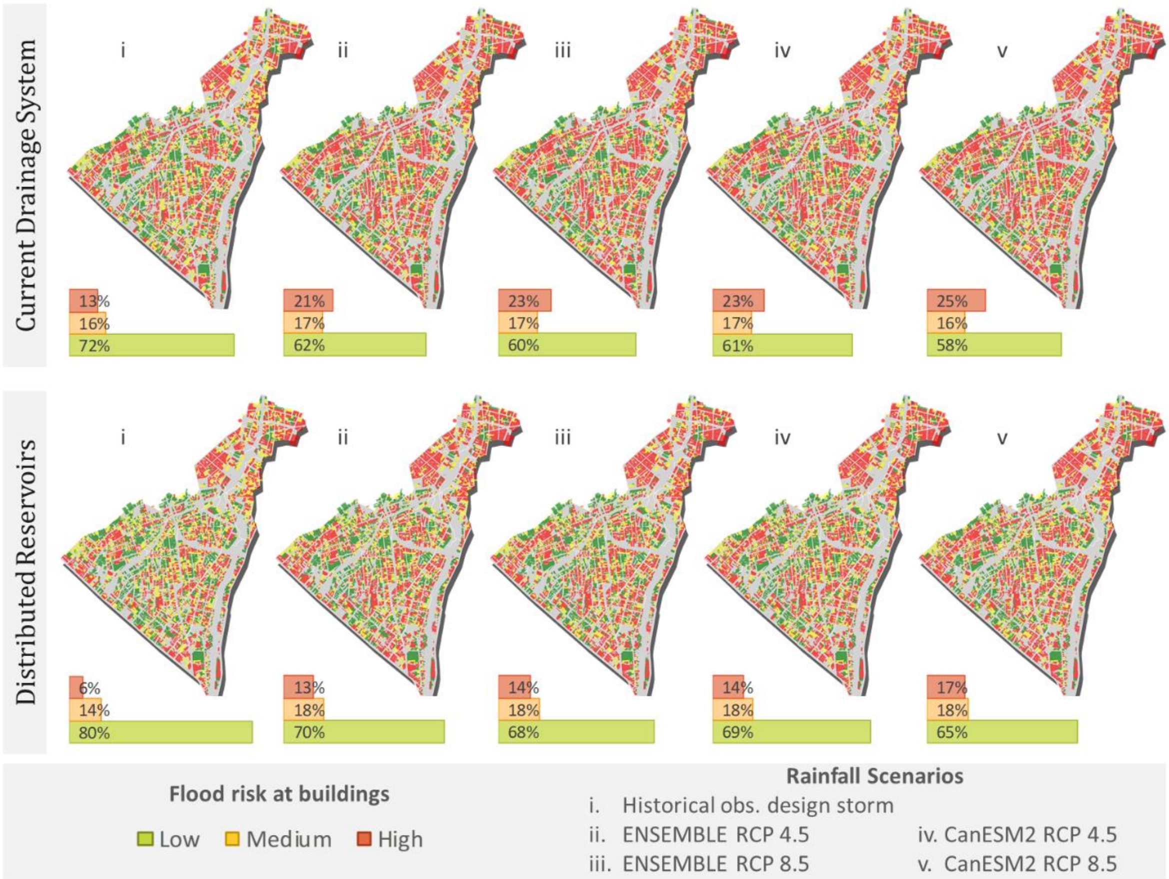

Figure 11. Flood risk analysis of buildings, 25-year return period.

The results of the flood risk analysis of buildings for both current and distributed storage system and LIDs are presented in Figure 12, comparing the different rainfall scenarios considering return periods of 25 years and 100 years. The devices adopted in the drainage system show improved efficiency and reduced risk in buildings and danger; at the same time, we can see that the climate change scenarios cause significant worsening of the performance of the drainage system.

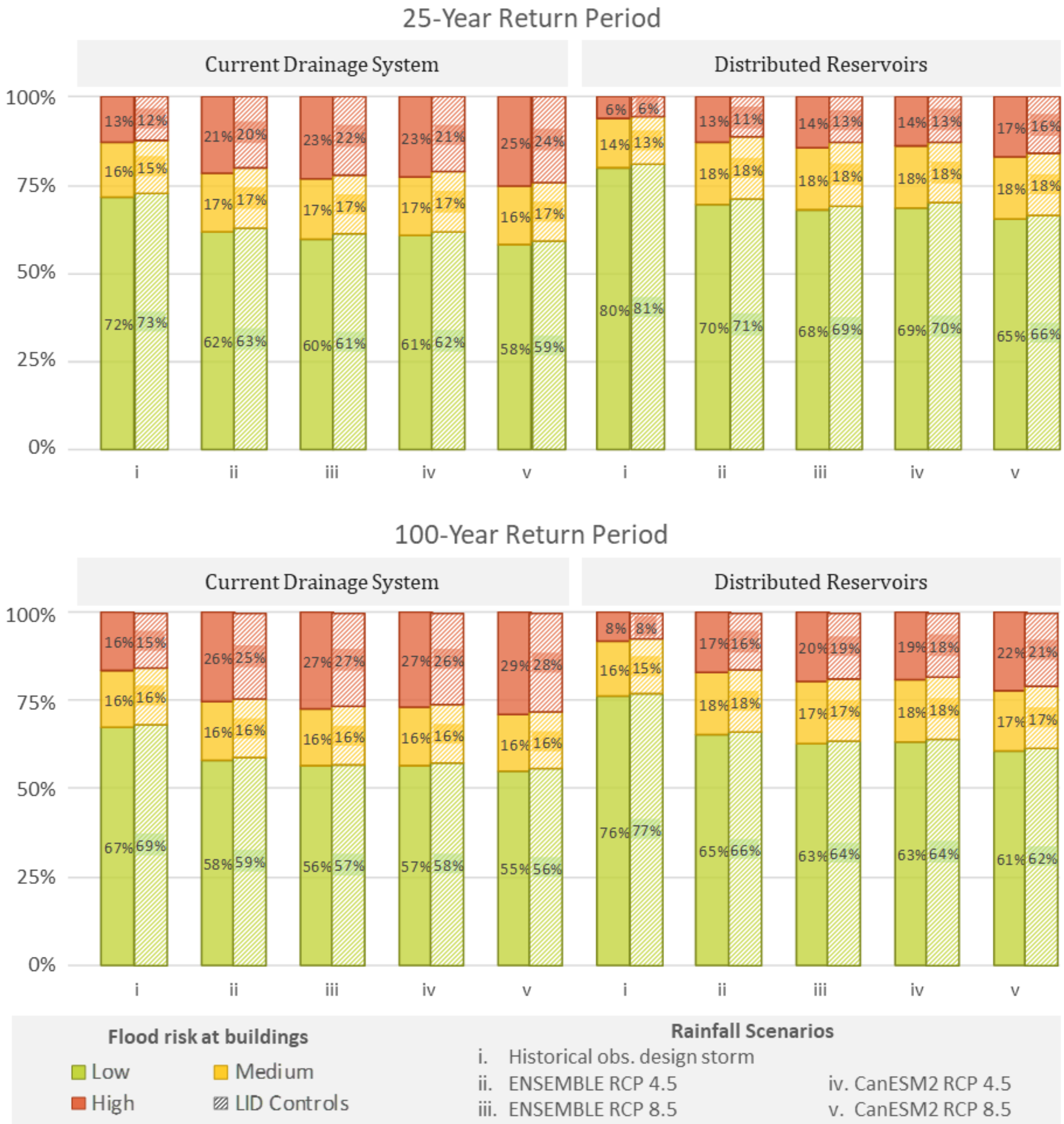

Figure 12. Flood risk analysis of buildings, result comparison of 25- and 100-year return periods.

4. Conclusions

For the current basin situation, floods with high hazard levels are centered in the valley bottoms along Avenida 9 de Julho, Praca da Bandeira, and Anhangabau tunnel; however, the problem is also distributed along several avenues and points throughout the basin.

To mitigate flooding in the watershed presented in this study, a distributed storage system was verified using a simulation model with very detailed representations of the drainage system and urban elements. The current capacity of the drainage system and proposed alternative were combined with LID controls. The alternative drainage system and LID controls were used to evaluate different design storm scenarios with return periods of 25 and 100 years as well as the updated IDF under climate change for RCP 4.5 and RCP 8.5.

The results presented show that the distributed storage system is an effective tool to reduce flooding in the region, especially for the scenarios based on existing IDF curves. However, scenarios where updated IDF curves under climate change were applied show that, even with implementation of the proposed improvements to the system, flooding and hazard conditions will not be drastically improved, especially for scenarios with higher emissions, such as RCP 8.5.

This may be deceiving for residents who are fully aware of the dramatic effects of climate change on highly populated urban areas. The distributed storage system proposed is not sufficient to mitigate the flooding issue in the presented case study, should the changing climatic conditions materialize. As mentioned, city planners and stakeholders need to take immediate action to prevent further increase and frequency of flooding in the region. Other alternatives should also be explored, such as further extending the retention system and implementing other LID control measures. Population awareness is no doubt necessary as a key to improving community resilience to recurrent and unavoidable flood events in the basin.

Author Contributions: J.I.B.G., C.F.V.d.S. and C.d.P.M.O. conceived and designed the model. A.S. and J.I.B.G. designed of the climate change scenarios and all authors assisted with writing and reviewing the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to acknowledge LabSid—*Laboratório de Sistemas de Suporte a Decisões* of the University of Sao Paulo and FCTH—*Fundação Centro Tecnologico de Hidráulica* for the support provided for the research, as well as the City of Sao Paulo for providing the spatial datasets. We are also grateful to the anonymous reviewers for their useful comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Silva, C.V.F.; Oliveira, C.P.M.; Garcia, J.I.B.; Yazaki, L.F.O.L.; Natale, O.; Brites, A.P.Z. Scenario Evaluation of Alternatives for Flood Control in the Anhangabaú Watershed, Brazil. In Proceedings of the 6th International Conference on Flood Management, São Paulo, Brazil, 16–18 September 2014; ABRH: Nashville, TN, USA, 2014.
2. Schardong, A.; Srivastav, R.K.; Simonovic, S.P. Update of the intensity-duration-frequency equation for the city of São Paulo under the effect of climate change. *RBRH* **2014**, *19*, 176–185. [CrossRef]
3. Marengo, J.A.; Chou, S.C.; Kay, G.; Alves, L.M.; Pesquero, J.F.; Soares, W.R.; Tavares, P. Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: Climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. *Clim. Dyn.* **2011**, *38*, 1829–1848. [CrossRef]
4. Semadeni-Davies, A.; Hernebring, C.; Svensson, G.; Gustafsson, L.G. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system. *J. Hydrol.* **2008**, *350*, 100–113. [CrossRef]
5. Hinkel, J.; Lincke, D.; Vafeidis, A.T.; Perrette, M.; Nicholls, R.J.; Tol, R.S.J.; Marzeion, B.; Fettweis, X.; Ionescu, C.; Levermann, A. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. USA* **2014**, 3292–3297. [CrossRef] [PubMed]
6. Muis, S.; Güneralp, B.; Jongman, B.; Aerts, J.C.J.H.; Ward, P.J. Flood risk and adaptation strategies under climate change and urban expansion: A probabilistic analysis using global data. *Sci. Total Environ.* **2015**, *538*, 445–457. [CrossRef] [PubMed]
7. Muller, M. Adapting to climate change: Water management for urban resilience. *Environ. Urban* **2007**, *19*, 99–113. [CrossRef]
8. Seidou, O.; Ramsay, A.; Nistor, I. Climate change impacts on extreme floods I: Combining imperfect deterministic simulations and non-stationary frequency analysis. *Nat. Hazards* **2012**, *61*, 647–659. [CrossRef]
9. Szewranski, S.; Kazak, J.; Żmuda, R.; Wawer, R. Indicator-based assessment for soil resource management in the Wroclaw larger urban zone of Poland. *Pol. J. Environ. Stud.* **2017**, *26*, 2239–2248. [CrossRef]
10. Zhou, Q.; Mikkelsen, P.S.; Halsnaes, K.; Arnbjerg-Nielsen, K. Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. *J. Hydrol.* **2012**, *414*, 539–549. [CrossRef]

11. Chang, H.K.; Tan, Y.C.; Lai, J.S.; Pan, T.Y.; Liu, T.M.; Tung, C.P. Improvement of a drainage system for flood management with assessment of the potential effects of climate change. *Hydrol. Sci. J.* **2013**, *58*, 1581–1597. [CrossRef]
12. Abdellatif, M.; Atherton, W.; Alkhaddar, R.; Osman, Y. Flood risk assessment for urban water system in a changing climate using artificial neural network. *Nat. Hazards* **2015**, *79*, 1059–1077. [CrossRef]
13. Zhou, Q.; Leng, G.; Huang, M. Impacts of future climate change on urban flood volumes in Hohhot in northern China: Benefits of climate change mitigation and adaptations. *Hydrol. Earth Syst. Sci.* **2018**, *22*, 305–316. [CrossRef]
14. Hammond, M.J.; Chen, A.S.; Djordjević, S.; Butler, D.; Mark, O. Urban flood impact assessment: A state-of-the-art review. *Urban Water J.* **2015**, *12*, 14–29. [CrossRef]
15. U.S. Environmental Protection Agency (US EPA). *SWMM 5 Applications Manual*; EPA/600/R-09/000; National Risk Management Research Laboratory, Office of Research and Development: Cincinnati, OH, USA, 2009.
16. U.S. Environmental Protection Agency (US EPA). *Storm Water Management Model Reference Manual Volume III–Water Quality*; EPA/600/R-16/093; National Risk Management Research Laboratory, Office of Research and Development: Cincinnati, OH, USA, 2016.
17. Jackisch, N.; Markus Weiler, M. The hydrologic outcome of a Low Impact Development (LID) site including superposition with streamflow peaks. *Urban Water J.* **2017**, *14*, 143–159. [CrossRef]
18. Rosa, D.J.; John, C.C.; Michael, E.D. Calibration and Verification of SWMM for Low Impact Development. *J. Am. Water Res. Assoc. (JAWRA)* **2015**, *51*, 746–757. [CrossRef]
19. CHI. PCSWMM. 2018. Available online: https://www.pcswmm.com/ (accessed on 8 June 2018).
20. Rossman, L.; Huber, W. *Storm Water Management Model Reference Manual Volume I, Hydrology*; EPA/600/R-15/162A; US EPA Office of Research and Development: Washington, DC, USA, 2015.
21. U.S. Environmental Protection Agency (US EPA). *Storm Water Management Model Reference Manual Volume III—Water Quality*; EPA/600/R-16/093; National Risk Management Research Laboratory, Office of Research and Development: Cincinnati, OH, USA, 2016.
22. Gironas, J.; Roesner, L.; Rossman, L.A.; Davis, J. A new applications manual for the Storm Water Management Model (SWMM). *Environ. Model. Softw.* **2010**, *25*, 813–814. [CrossRef]
23. Song, J.Y.; Chung, E.S. A multi-criteria decision analysis framework for prioritizing sites and types of low impact development practices. *Water* **2017**, *9*, 291. [CrossRef]
24. Ahiablame, L.; Shakya, R. Modeling flood reduction effects of low impact development at a watershed scale. *J. Environ. Manag.* **2016**, *171*, 81–91. [CrossRef] [PubMed]
25. Aryal, S.K.; Ashbolt, S.; McIntosh, B.S.; Petrone, K.P.; Maheepala, S.; Chowdhury, R.K.; Gardener, T.; Gardiner, R. Assessing and mitigating the hydrological impacts of urbanisation in semi-urban catchments using the storm water management model. *Water Resour. Manag.* **2016**, *30*, 5437–5454. [CrossRef]
26. Cipolla, S.S.; Maglionico, M.; Stojkov, I. A long-term hydrological modelling of an extensive green roof by means of SWMM. *Ecol. Eng.* **2016**, *95*, 876–887. [CrossRef]
27. Yang, Y.; Chui, T.F.M. Rapid Assessment of Hydrologic Performance of Low Impact Development Practices under Design Storms. *J. Am. Water Resour. Asso.* **2018**, *54*, 613–630. [CrossRef]
28. Liu, Y.; Bralts, V.F.; Engel, B.A. Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model. *Sci. Total Environ.* **2015**, *511*, 298–308. [CrossRef] [PubMed]
29. Tomaz, P. Hydrological and Hydraulic Calculations for Municipal Works. *Navegar* **2012**. (In Portuguese)
30. Millington, N.; Samiran, D.; Simonovic, S.P. *The Comparison of GEV, Log-Pearson Type 3 and Gumbel Distributions in the upper Thames River Watershed under Global Climate Models*; Water Resources Research Report No. 077; Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering: London, UK; Ontario, ON, Canada, 2011; p. 53. ISBN 978-0-7714-2898-2.
31. Hosking, J.R.M.; Wallis, J.R. *Regional Frequency Analysis*; Cambridge University Press: Cambridge, UK, 1997.
32. Schardong, A.; Simonovic, S.P.; Sandink, D. *Computerized Tool for the Development of Intensity-Duration-Frequency Curves under a Changing Climate: Technical Manual v.3*; Water Resources Research Report No. 103; Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering: London, UK; Ontario, ON, Canada, 2018; p. 67. ISBN 978-0-7714-3107-4.

33. Martinez Junior, F.; Magni, N.L.G. *Equations of intense rainfall in the State of Sao Paulo*; Department of Water and Electric Power, Polytechnic School of the University of Sao Paulo: Sao Paulo, Brazil, 1999; p. 125. (In Portuguese)
34. Simonovic, S.P.; Schardong, A.; Sandink, D.; Srivastav, R. A Web-based Tool for the Development of Intensity Duration Frequency Curves under Changing Climate. *Environ. Model. Softw. J.* **2016**, *81*, 136–153. [CrossRef]
35. Sandink, D.; Simonovic, S.P.; Schardong, A.; Srivastav, R. A Decision Support System for Updating and Incorporating Climate Change Impacts into Rainfall Intensity-DurationFrequency Curves: Review of the Stakeholder Involvement Process. *Environ. Model. Softw. J.* **2016**, *84*, 193–209. [CrossRef]
36. Schardong, A.; Simonovic, S.P.; Sandink, D. *Computerized Tool for the Development of Intensity-Duration-Frequency Curves under a Changing Climate: User's Manual v.3*; Water Resources Research Report No. 104; Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering: London, UK; Ontario, ON, Canada, 2018; p. 80. ISBN 978-0-7714-3108-1.
37. Abt, S.R.; Wittler, R.J.; Taylor, A.; Love, D.J. Human stability in a high flood hazard zone. *Water Res. Bull.* **1989**, *25*, 881–890. [CrossRef]
38. Jonkman, S.N.; Vrijling, J.K.; Vrouwenvelder, A.C.W.M. Methods for the estimation of loss of life due to floods: A literature review and a proposal for a new method. *Nat. Hazards* **2008**, *46*, 353–389. [CrossRef]
39. Shand, T.D.; Smith, G.P.; Cox, R.J.; Blacka, M. Development of Appropriate Criteria for the Safety and Stability of Persons and Vehicles in Floods. In Proceedings of the 34th IAHR Conference, Brisbane, Australia, 26 June–1 July 2011.
40. Russo, B.; Gómez, M.; Macchione, F. Pedestrian hazard criteria for flooded urban areas. *Nat. Hazards* **2013**, *69*, 251–265. [CrossRef]