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Stormwater Harvested from Permeable Pavements as a Means to Save Potable Water in Buildings

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Abstract: The main objective of this work is to analyse the potential for potable water savings in university buildings by using stormwater collected from permeable pavements. Six buildings located on the campus of the Federal University of Santa Catarina (UFSC) were selected to obtain monthly water consumption patterns and parking lot areas. The same six buildings were then evaluated considering their location in eight different cities in Brazil, with different rainfall patterns. Simulations using the computer programme Netuno were run to obtain the potential for potable water savings in each building and city combined. The structural design of permeable pavements was also assessed using two methods available in the literature, that is, the American Association of State Highway and Transportation Officials (AASHTO) and Brazilian Portland Cement Association (ABCP). The hydrological-hydraulic design of the permeable pavement was also carried out. The designed thicknesses were compared with the thicknesses obtained using the computer programme Permeable Design Pro. The potential for potable water savings between 18.4% and 84.8% was obtained, depending on the city, building and non-potable water demand considered. For the structural design, the thicknesses obtained by using both methods were similar; however, it was observed that the AASHTO method better represents the pavement model. Regarding the hydrological-hydraulic design, the differences obtained show that the simplification performed for the pavement drainage was in favour of safety. In conclusion, the use of permeable pavements in stormwater harvesting systems is promising, aligning the drainage aid, structural capacity and potential for saving potable water.

Keywords: permeable pavements; potable water savings; universities; public buildings; stormwater harvesting; sustainability

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1. Introduction

Climate change is evident in the urban environment. The increase in global temperature correlates with the increase in rainfall peak intensity, which facilitates the occurrence of urban flooding [1]. On the other hand, changes in rainfall patterns have made water management more difficult, affecting the amount of water available. As an example, Cape Town in South Africa had the worst drought in its history in 2015, limiting water consumption to 50 L per day per inhabitant [2]. São Paulo also experienced one of the worst droughts in its history in 2014, which resulted in actions on water management and rationing among users [2,3].

According to the Intergovernmental Panel on Climate Change (IPCC) [4], in 2012, Earth had a temperature increase of 0.85 °C compared to the pre-industrial average. According to the IPCC [5], if fast and deep changes are not adopted, the temperature increase may be higher than 1.5 °C by 2100. Amidst the uncertainties of future weather conditions, the use of alternative sources of water will become necessary. Alternative sources, such as rainwater, greywater, seawater and the use of water-efficient systems, are examples of measures that can be applied [6]. Rainwater harvesting in buildings is already a legal requirement in some cities around the world. We can mention the city of Curitiba, in Brazil, which in 2006 approved a decree that provides the criteria for the rational use and conservation of water in buildings. Thus, for the licensing of new constructions in the city, rainwater harvesting became mandatory, being treated and used for non-potable purposes [7].

Potable water savings through the use of rainwater combines the possibility of monetary savings for users and future security against water scarcity. In sustainable terms, the water utilities save chemical products used in water treatment and energy from pumping water, as less water is demanded. Some studies have verified the potential for potable water savings in buildings, as well as the investment feasibility analysis, such as Anand and Apul [8], Ghisi et al. [9] and Marinoski et al. [10], among others.

Another problem that can arise from anthropic intervention in the environment is the change in hydrological patterns due to high soil sealing. The water that once infiltrated the soil and drained towards the water table now becomes runoff in the streets, roofs and gutters. This factor is related to the increase in peak flow, which has a direct impact on urban drainage, which can end up overloaded. Other factors, such as the presence of sewage in drainage devices, may also be crucial to the presence of flooding [11].

Sustainable Urban Drainage Systems (SUDS) try to recover urban drainage through systems more adapted to the hydrological cycle. Examples of SUDS applications include the use of green roofs, infiltration trenches and permeable pavements [12]. SUDS avoid peak flow, which may occur in a centralised system of drainage galleries. Other terms that can be related to SUDS [11] are Low Impact Development (LID) and Water Sensitive Urban Design (WSUD).

Permeable pavement is one type of system that is described as SUDS [13]. The permeable capacity of the pavement takes up part of the permeability removed by the waterproofing of the urban surface, and this helps to reduce the peak flows [14]. The Brazilian Association of Portland Cement (ABCP, in Portuguese) indicates the use of permeable pavements for residential, commercial and industrial patios, parking lots, sidewalks and light traffic roads [15].

Other positive aspects of the application of permeable pavements are oil and grease retention [16], heavy metal retention [17], the reduction of the amount of runoff in the road [18] and the reduction of the noise emitted by vehicles [19]. Therefore, the use of permeable pavements is favourable not only in hydrological terms, adapting better to the natural cycle of water, but also to the user. Permeable pavements avoid the accumulation of water in puddles and wheel tracks, avoid pollution diffusion in water that can come into contact with the user, and can even suppress noise pollution.

Some recent studies have assessed how the combination of permeable pavements and stormwater harvesting performs. There is a concern about the quantity [20,21] and the quality of stormwater harvested [20,22,23] in order to be applicable in sustainable design approaches. Some other concerns include the Life Cycle Assessment (LCA) of the technique, which is crucial to understanding the environmental impacts and benefits of its application [24,25].

2. Materials and Methods

2.1. Simulation Variables

The study began with the selection of six buildings, eight cities and the corresponding water end-uses. After obtaining the water consumption data and the built area of the six buildings, daily rainfall and Intensity-Duration-Frequency (IDF) equations for the eight cities were analysed. The potential for potable water savings in each scenario was evaluated using the Netuno 4 computer programme. The results obtained were grouped and analysed in order to assess the influence of the three parameters on the potential for potable water savings.

After the simulation of potable water savings, the hydrologic/hydraulic design was performed according to a method from the literature. Computer routines were performed using the GNU Octave programming language in order to simplify the process. The results obtained were then compared with those obtained from the Permeable Design Pro programme.

A computational routine was also proposed for the structural design of the pavement, based on the American Association of State Highway and Transportation Officials (AASHTO) method [26]. The results obtained with the routine for the AASHTO method were compared with the thicknesses indicated by the Permeable Design Pro computer programme in order to validate the routine. The design was also performed using the Brazilian Portland Cement Association (ABCP) method [27], a method used in Brazilian designs.

2.1.1. Rainwater Harvesting Model

The rainwater harvesting model was carried out based on models available in the literature. Some authors [24,25] have proposed a permeable pavement water harvesting system composed of: a catchment area, the permeable pavement, underground and upper rainwater tanks and water pumping station. Rainwater falls over the pavement, infiltrates through the permeable layers and it is conducted via drains towards the underground tank. When the upper rainwater tank is about to become empty, that is, less than 10% of its capacity, rainwater from the underground tank is pumped to fill it up. If there is no rainwater available in the underground tank, potable water from the building's water tank is conducted towards the upper rainwater tank by gravity. If both upper and underground rainwater tanks are full, rainwater is discarded in the drainage system. Figure S1 in the Supplementary Materials shows a schematic of the system. Water treatment—chlorination only—is applied in the upper rainwater tank in order to avoid waste of treated rainwater.

2.1.2. Permeable Pavement Model

The permeable pavement model used in the study was based on previous research [28], which made models of a permeable pavement using permeable concrete pavers. The main reason for using data from actual physical models is to be able to guarantee that the simulated pavers exist on the market. The infiltration rate obtained by Ghisi et al. for concrete pavers was 710 cm/h [28], which is approximately twice the lower limit of the Brazilian standards [29], that is, 360 cm/h for permeable coating.

Figure 1 shows the pavement layers used in the study with the following specifications:

- Reservoir course: Gravel ASTM #2 and thickness according to design;
- Choker course: Gravel ASTM #57 and thickness equal to 30 mm;
- Bedding course: Gravel ASTM #8 and thickness equal to 30 mm;
- Permeable concrete pavers: Dimensions equal to 200 mm in length, 100 mm in width and 80 mm in thickness. Thickness was defined as 80 mm instead of 60 mm, as used in Ghisi et al.'s model [28], in order to comply with Brazilian standards [29].

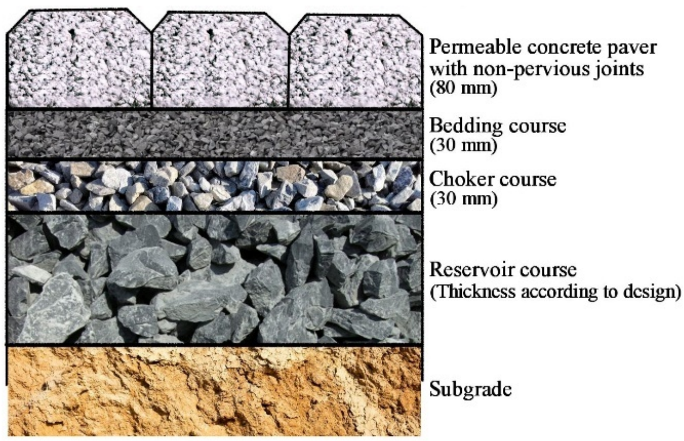

Figure 1. Permeable pavement model used in the study.

2.1.3. Buildings

Six university buildings were chosen for the study. They were chosen to represent different built areas and water consumption, and also for having a parking lot area nearby. All buildings were part of the Federal University of Santa Catarina (UFSC). Table 1 shows the six buildings and their parking lot areas and water consumption.

Table 1. Parking lot area and water consumption for the six buildings.

Building	Parking Lot Area (m^2)	Water Consumption (L/year)
University Library	3150	3899
Department of Civil Engineering	1600	1540
Department of Architecture and Engineering Projects	1750	322
Department of Architecture and Urbanism	2050	4541
University Administration Building	1650	4089
Technology Centre	5500	4953

Source: Based on [30,31].

The decision to choose university buildings takes into account two points. The first is that the non-potable water end-uses in this type of building are usually higher than in residential buildings. As examples, the studies of Botelho [32] and Rainmap [33] found that the non-potable water end-uses of the UFSC Technology Centre were equal to 69% and 70%, respectively. The second point is the current Brazilian context, in which there are budgetary difficulties in the academic environment and the need for the reduction of expenses. In 2018, for example, UFSC spent approximately 7.3 million reais (R$) on water bills [30].

2.1.4. Cities

The eight Brazilian cities were chosen taking into account that they have a public university. Table 2 shows the different characteristics of the cities and Figure 2 shows the location of the cities on the map of Brazil.

Table 2. Characteristics of the eight cities.

City	Population	Area (Km^2)	Latitude	Longitude
Manaus	2,182,763	11,401.092	−3.10719	−60.0261
Recife	1,645,727	218.843	−8.05428	−34.8813
Brasília	3,015,268	5760.783	−15.7801	−47.9292
Belo Horizonte	2,512,070	331.401	−19.8157	−43.9542
São Paulo	12,252,023	1521.110	−23.5489	−46.6388
Curitiba	1,933,105	435.036	−25.4284	−49.2733
Florianópolis	500,973	674.844	−27.5969	−48.5495
Porto Alegre	1,483,771	495.390	−30.0277	−51.2287

Source: Based on [34].

Figure 2. Location of the cities used in the study. Source: [31] for background image.

2.2. *Potable Water Savings*

The simulations to evaluate the potential for potable water savings were carried out using the Netuno 4 computer programme [35]. Eight variables were considered, that is, daily rainfall, harvesting area, total water demand, rainwater demand, infiltration coefficient, upper rainwater tank capacity and underground rainwater tank capacity.

Netuno 4 is a computer programme, created by Ghisi and Cordova [35], used for sizing rainwater tanks and estimating the potential for potable water savings when there is rainwater harvesting. The simulation uses defined variables, that is, it does not rely on a stochastic model of variables and statistical outputs. The main use and definitions are for rooftop rainwater harvesting, but it has all the necessary inputs for a water balance simulation, which can be applied similarly in the permeable pavement system design.

2.2.1. Daily Rainfall

Rainfall data from 2003 to 2017 were obtained through the Meteorological Database for Education and Research (BDMEP) [36] of Brazil, in CSV format. The first flush was set to zero since the permeable pavement is meant to be used to filter the stormwater and there are no diverters for the first flush.

2.2.2. Harvesting Area

The harvesting area refers to all areas that contribute to the volume of rainwater harvested. For all six buildings, the areas of the parking lot and impermeable surrounding surfaces were considered, that is, the total harvesting area was equal to the sum of permeable and impermeable surfaces. The water on the impermeable surface flows towards the permeable pavement and then infiltrates it.

2.2.3. Total Water Demand

The total water demand in the building refers to all water consumption during a given period—daily, monthly or yearly. Thus, for each of the six buildings, the average monthly consumption was obtained through a historical series of water consumption data. Data were obtained via compiled files from the UFSC's monitoring of water supply and sanitation [30].

Monthly water consumption was converted to daily data in order to be used in Netuno 4. This procedure was carried out by dividing the monthly consumption by the number of working days in each month plus one day. This extra day was to take into account the weekend; it was considered that all the weekend days in a month represent one working day. This consideration was made based on the fact that the university has a higher occupation over the week. Thus, consumption on a weekend day represents between 10.0% and 12.5% of the consumption on a working day. Equation (1) shows the consumption on a weekday, and Equation (2) shows the consumption on a weekend day.

$$Dcwi_i = \frac{Mc_i}{(wdi_i + 1)}, \tag{1}$$

$$Dcwk_i = \frac{Mc_i}{(wdi_i + 1) \times wk_i}, \tag{2}$$

where: $Dcwd_i$ is the daily consumption on working days in the month i (L/day); Mc_i is the monthly consumption in the month i (L/month); $Dcwk_i$ is the daily consumption on weekends in the month i (L/day); wd_i is the number of working days in the month i (days); wk_i is the number of weekend days in the month i (days).

2.2.4. Rainwater Demand

Rainwater demand represents the part of the total water demand that requires non-potable water. It is one of the parameters required by Netuno 4 to indicate the maximum potential for potable water savings that the system can obtain. It is related to the percentage of water end-uses that can be supplied with non-potable water, such as toilets, urinals and garden irrigation.

The Brazilian standard for non-potable water uses in buildings is NBR 16783 [37]. The possible non-potable uses included in the standard are car washing, toilet flushing, urinal flushing, cleaning of outside areas, irrigation, ornamental use and cooling. For these specific uses, the standard generally addresses seven quality parameters (pH, Escherichia coli, turbidity, biochemical oxygen demand, residual chlorine, electrical conductivity or total dissolved solids, and total organic carbon); for other uses it requires a specific study of quality parameters depending on the water source.

In this study, three rainwater demands were considered based on the studies of Botelho [32], Rainmap [33] and also on a survey carried out at UFSC library in 2018, which was not published. Based on such studies, three rainwater demand scenarios were analysed, that is, 69%, 77% and 85% of the total water demand.

2.2.5. Infiltration Coefficient

The infiltration coefficient refers to the percentage of stormwater that is harvested in relation to the amount of stormwater that falls onto the harvesting area. Since this study deals with permeable pavements, the infiltration coefficient refers to the relationship between the amount of stormwater that falls onto the pavement and the amount that reaches the lower rainwater tank. The value used in the study was the same as that obtained by Ghisi et al. [28] in their study on permeable pavements with pervious concrete pavers, that is, 88.1%.

2.2.6. Upper Rainwater Tank

It was defined that the upper rainwater tank in each building has a capacity equal to the average daily rainwater demand for that building. For the pumping pattern, it was defined that the pump will be turned on every time the amount of water in the upper rainwater tank reaches 10% of its total capacity.

2.2.7. Underground Rainwater Tank

The pavement will serve as a filter for stormwater and also as temporary storage, but the bottom drains in the reservoir course direct the stormwater to the underground rainwater tank. The capacity of the underground rainwater tank was sized using Netuno 4.

As the programme iterates in the simulations, it calculates the potential for potable water savings and, from the results, indicates the optimal rainwater tank capacity.

The simulations were performed for underground rainwater tank capacities ranging from 0 to 50,000 L at intervals of 1000 L. For each lower tank capacity, a different potential for potable water savings was obtained. An optimal rainwater tank capacity was defined as a function of the potential for potable water savings and the underground rainwater tank capacity, that is, an added potential lower than $1\%/m^3$.

2.3. Hydrologic/hydraulic Design

The hydrologic/hydraulic design consists of defining the thickness of the reservoir course layer. It was performed for each of the eight Brazilian cities in order to size for the city's design rainfall, which was obtained via the Intensity-Duration-Frequency (IDF) equation or the design rainfall height. The ratio between the permeable area and the impermeable area of the pavement was assessed for each building. Another relevant point is the definition of the pavement bottom drain, which serves for the specific outlet flow and influences the thickness required for the reservoir course.

2.3.1. IDF Equations

The IDF equations are necessary for assessing design rainfall, which is used in the design of any type of hydraulic structure. The knowledge about design rainfall is necessary for making the structures compatible with future rainfall demands. As far as design rainfall is concerned, according to Back [38], some methods can be used to define the rainfall curve mathematically. In Brazil, the IDF curve is usually used.

The IDF equations were used in the potential format, as shown in Equation (3). Table 3 shows the IDF curve parameters of each of the eight cities.

$$i = \frac{K \times T^m}{(t+d)^n}, \tag{3}$$

where: K, m, n and d are coefficients that vary according to the place; T is the return period (years); i is the average maximum intensity of the design rainfall (mm/h); and t is the duration of the design rainfall (minutes).

Table 3. Intensity-Duration-Frequency variables used in the hydrological design in each city.

City	Source	Variables			
		K	m	d	n
Manaus	Souza and Azevedo [39]	1701.340	0.110	25.00	0.798
Recife	CPRM [40]	4247.900	0.210	25.20	1.120
Brasília	Silva et al. [41]	1646.120	0.128	15.72	0.856
Belo Horizonte	ADASA [42]	1574.700	0.207	11.00	0.884
São Paulo	Fendrich [43]	5950.000	0.217	26.00	1.150
Curitiba	CPRM [44]	3221.070	0.258	26.00	1.010
Florianópolis	Back and Bonetti [45]	1168.500	0.238	9.10	0.703
Porto Alegre	Freitas et al. [46]	682.874	0.169	3.99	0.671

To calculate the average maximum intensity using the IDF equations, it is also necessary to define the duration of the rainfall and the return period. The return period and duration of rainfall have been chosen according to Brazilian standards [29]. The minimum return period was taken to be ten years, with a minimum duration of rainfall equal to 60 min.

2.3.2. Permeable to Impermeable Area Ration (R)

Another important parameter for performing the hydrologic/hydraulic design is the ratio between the total area and the permeable area of the pavement. Equation (4) shows how the ratio parameter (R) was calculated. R values between 1 and 2 can be used, that is, the impermeable area can range from zero to a figure equal to the permeable pavement area, not exceeding it [47].

$$R = \frac{A_{per} + A_{imp}}{A_{per}}, \tag{4}$$

where: R is the ratio of the total area to the permeable area (dimensionless); A_{per} is the area of the permeable surface (m^2); and A_{imp} is the area of the impermeable surface (m^2).

For each building, parking lot sketches were made in order to estimate R. The pavement slope turns the runoff towards the edges of the track, where there is drainage through the permeable pavement. Figure S2 in the Supplementary Materials shows the sketch of the Technology Centre parking lot, as an example.

2.3.3. Bottom Drains

The specific output flow is the hydrologic/hydraulic design parameter that defines the drainage capacity after infiltration into the pavement. Hammes et al. (2018) used a simplified method to evaluate the specific output flow, defining it as a constant figure, which corresponds to the total amount of water falling on the floor divided by the permeable area over 24 h. The time necessary to empty the reservoir course was defined by Hammes et al. [20], based on Tomaz [48], as at least 24 h. Equation (5) shows the simplified method for calculating the specific output flow, which was used herein.

$$q_s = \frac{i \times t \times A_{tot}}{A_{per} \times TE \times 1000}, \tag{5}$$

where: q_s is the specific output flow (m/h); i is the average maximum rainfall intensity (mm/h); t is the duration of the design rainfall, considered equal to 1 h (h); A_{tot} is the total pavement area (m^2); A_{per} is the permeable pavement area (m^2); and TE is the time necessary to empty the reservoir course (h).

2.3.4. Hydrologic/hydraulic Design Method

The method of Hammes et al. [20] was used herein for hydrologic/hydraulic design. The method is very similar to that in the Tennessee Permanent Stormwater Management and Design Guidance Manual [47] and the Brazilian standard [29]. The result of the hydrologic design is the thickness of the reservoir course required for temporary rainwater storage. After the storage, the water is drained by gravity through underground drains to a lower rainwater tank; if the rainwater tank is full, the water flows into the drainage system. Equation (6) shows the method of Hammes et al. [20].

$$H_{rc} = \frac{\frac{t}{60} \times (R \times i - q_s \times 1000)}{\eta}, \tag{6}$$

where: H_{rc} is the required thickness of the reservoir course (mm); t is the duration of the design rainfall (min); R is the ratio of the total area to the permeable area (dimensionless); q_s is the constant specific outlet flow of the pavement (m/h); i is the average maximum intensity of the design rainfall (mm/h); and η is the porosity of the reservoir course (dimensionless).

2.4. Structural Design

The structural design of the permeable pavement is necessary in order to guarantee that the thickness of the layers is adequate to dissipate the stress generated by the traffic of vehicles. Two methods used for design were assessed: the ABCP method [27] and the AASHTO method [26]. The ABCP method is a simple design method that has as its input parameters the Equivalent Single Axle Load (ESAL) data, estimated for pavement life, and the California Bearing Ratio (CBR) of the subgrade. Only these two parameters are necessary to design the reservoir course. As a restriction for the subgrade material, the method indicates a minimum CBR equal to 20% for less than 500,000 ESALs, and 30% for more than 500,000 ESALs.

The AASHTO method requires more input parameters than the ABCP. The AASHTO parameters are: the number of ESALs, also estimated for the pavement's lifespan; subgrade CBR; thickness and material of all layers; pavement's drainage condition; Present Serviceability Index (PSI) and statistical parameters. It is a more comprehensive method, with application to flexible pavements in general, while the ABCP method is restricted to pavements with interlocking concrete pavement. The thickness and materials of the pavers, the bedding layer and choker course were chosen following the permeable pavement construction manuals [47,49] and the Brazilian standard [29]. Drainage coefficient, PSI and statistical parameters were chosen according to the AASHTO manual [26] in order to agree with the type of pavement and its use. Equations (7) and (8) show the AASHTO method for structural design.

$$\log_{10}(W_{18}) = Z_r \times S_o + 9.36 \times \log_{10}(SN+1) - 0.2 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.4 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10}(M_r) - 8.07, \quad (7)$$

$$SN = \sum_{i=1}^{n} a_{(i)} \times d_{(i)} \times m_{(i)}, \quad (8)$$

where: W_{18} is the number of ESALs over the pavement lifespan (dimensionless, 18 stands for the reference axle load of 18,000 lb); and Z_r is the number of standard deviations needed to obtain, in a standard normal distribution, the probability of structural failure. For example, at 95% reliability and 5% chance of failure, Z is -1.645 (dimensionless); S_o is the standard deviation of the supported value of traffic over the service life, taking into account the variability of construction, assumed parameters of materials and the assumed number of future vehicles the pavement will support (dimensionless); SN is the Structural Number of the pavement, which takes into account the thickness and materials of layers (inches); ΔPSI is the difference of Present Serviceability Index in the beginning and at the end of the pavement's life cycle (dimensionless); M_r is the resilient modulus of the subgrade layer (psi); $a_{(i)}$ is the structural coefficient of the pavement layer i (dimensionless); $d_{(i)}$ is the thickness of the pavement layer i (inches); $m_{(i)}$ is the drainage coefficient of the pavement layer i (dimensionless); n is the number of layers in the pavement.

As the AASHTO structural design method uses the resilient modulus of the layers, it was necessary to make a correlation between the resilient modulus and CBR to be able to compare with the ABCP method. Thus, the correlation shown in Equation (9) between CBR and the resilient modulus was used [50,51].

$$M_r = 2555 \times CBR^{0.64}, \quad (9)$$

where M_r is the Resilient Modulus (psi) and CBR is the California Bearing Ratio (dimensionless).

2.5. Model Validation

The permeable pavement was also designed using Interlocking Concrete Pavement Institute (ICPI) programme Permeable Design Pro [51]. The purpose was to compare the results obtained through the hydrologic/hydraulic design method found in the literature with those obtained from the programme. The programme uses an hourly analysis of mass balance in the hydrologic/hydraulic design.

3. Results and Discussion

3.1. Potential for Potable Water Savings

The potential for potable water savings was estimated for each combination of building, city and rainwater demand, totalling 144 simulations. The resulting analysis was performed in order to understand how these three parameters influence the potential for potable water savings.

3.1.1. Rainfall Data

Rainfall data were obtained for each of the eight cities and were treated and organised for better visualisation. Three main characteristics that differ among the cities were observed. The first is the average annual rainfall, which varied between 1454 and 2287 mm/year. Porto Alegre has the lowest annual rainfall and Manaus has the highest. The second characteristic is the distribution of monthly rainfall during the year. Some of the cities had a fairly constant monthly rainfall, while others had well defined dry and wet periods. As an example, Brasília has a dry period between May and September. The last characteristic observed is the maximum rainfall in one day, which was compared with the results obtained using the IDF curves, in order to understand whether the curves match the local rainfall profile. Table 4 shows the characteristics observed for each of the eight cities. Figures 3 and 4 show the minimum, average and maximum rainfall for Brasília and Porto Alegre, respectively. Figures S3–S8 in the Supplementary Materials show the minimum, average and maximum rainfall for the other cities studied herein.

Table 4. Rainfall data in each city over 2003–2017.

City	Average Annual Rainfall (mm/year)	Standard Deviation of Monthly Average Rainfall (m^3/Month)	Highest Daily Rainfall (mm/day)
Manaus	2287	100.31	142
Recife	2230	124.55	150
Brasília	1469	96.12	111
Belo Horizonte	1522	113.15	156
São Paulo	1641	84.71	140
Curitiba	1584	33.49	128
Florianópolis	1789	39.79	253
Porto Alegre	1454	16.73	150

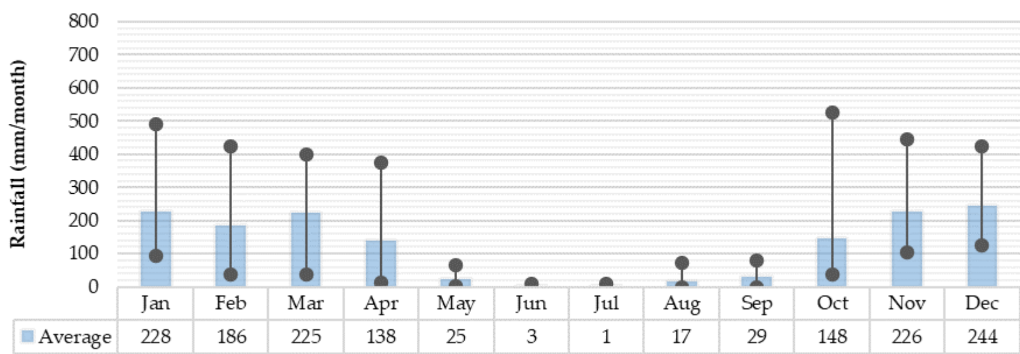

Figure 3. Average, minimum and maximum monthly rainfall in the city of Brasília over 2003–2017.

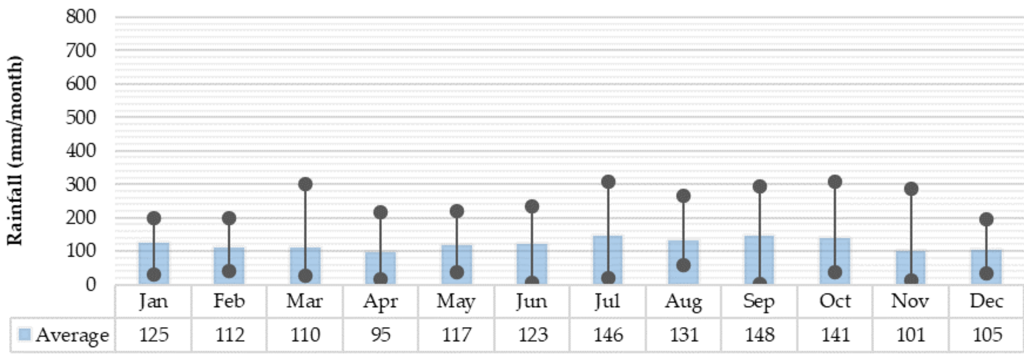

Figure 4. Average, minimum and maximum monthly rainfall in the city of Porto Alegre over 2003–2017.

3.1.2. Water Consumption

Water consumption was assessed in order to understand two points: differences in the consumption of the buildings over time and distribution of consumption during the year. The analysis of the variation over the years serves to check divergences due to leaks or retrofits in plumbing systems. The analysis of distribution during the year serves to create the daily water consumption model, used in the computer simulations. Figure S9 in the Supplementary Materials shows the water consumption for the six buildings. Figure 5 shows the monthly average water consumption during the year for the six buildings.

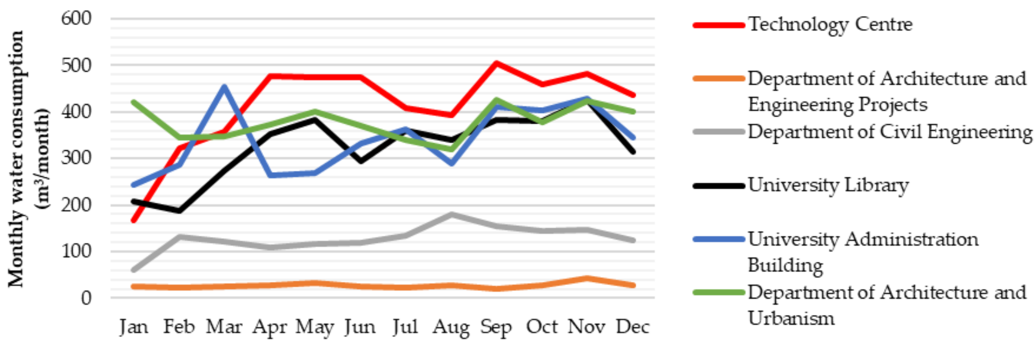

Figure 5. Monthly average water consumption in the six buildings.

Based on the monthly average water consumption in each building, it was possible to estimate the daily water consumption. Figure 6 shows, as an example, the daily water consumption of the Technology Centre building used as input data in the computer simulations. Figures S10–S14 in the Supplementary Materials show the daily water consumption for the remaining buildings.

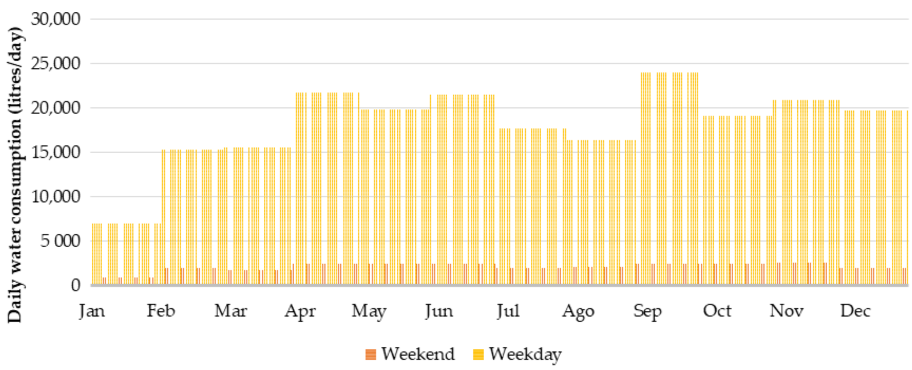

Figure 6. Daily water consumption in Technology Centre building considered in the computer simulations.

3.1.3. Potable Water Savings

Figure 7 shows, as an example, the potential for potable water savings for the six buildings in the city of Florianópolis considering the three different rainwater demands. The ideal underground tank capacity for the Technology Centre was 24,000, 21,000 and 23,000 L for rainwater demands equal to 69%, 77% and 85%, respectively. Figures S15–S21 in the Supplementary Materials show the results for the other cities.

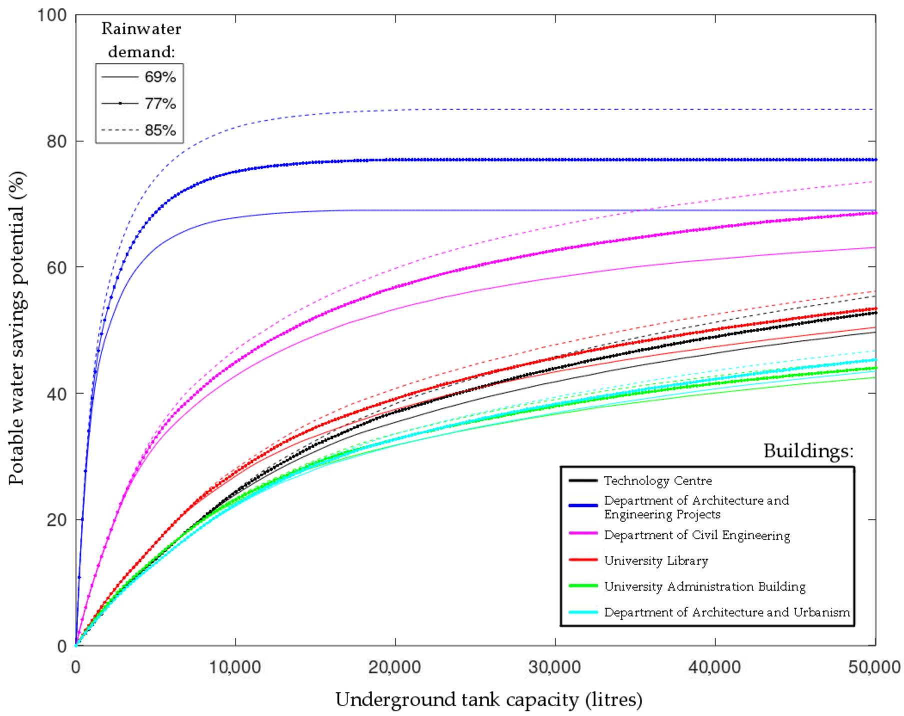

Figure 7. Potential for potable water savings for the six buildings located in Florianópolis.

Figure 8 summarises the average potential for potable water savings for the six buildings, eight cities and three rainwater demands. Such savings ranged from 18.48% to 82.81%. The lowest potential occurred in the architecture and urbanism building when the rainwater demand was equal to 69% of the total water consumption in Belo Horizonte. The highest potential for potable water savings occurred in the Department of Architecture and Engineering Projects building when the rainwater demand was equal to 85% of the total water consumption in Florianópolis. Table 5 shows, as an example, the optimal underground tank size for each building in Florianópolis.

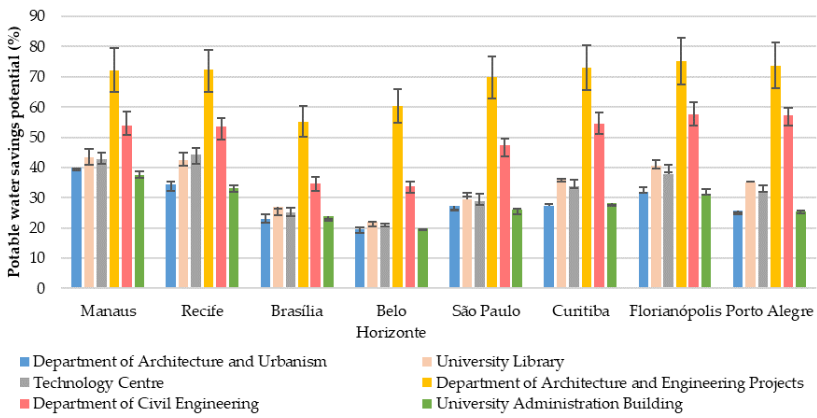

Figure 8. Potable water savings potential for the average rainwater demand (77%), minimum (69%) and maximum (85%).

Table 5. Optimal underground tank capacity, rainfall and harvesting area for Florianópolis.

Building	Annual Average Rainfall (mm/year)	Total Harvesting Area (m^2)	Optimal Underground Tank Capacity (m^3) for Each Rainwater Demand		
			69%	77%	85%
University Library	1789	3150	23.0	22.0	22.0
Department of Civil Engineering		1600	21.0	21.0	22.0
Department of Architecture and Engineering Projects		1750	9.0	10.0	11.0
Department of Architecture and Urbanism		2050	20.0	19.0	20.0
University Administration Building		1650	19.0	18.0	19.0
Technology Centre		5500	24.0	21.0	23.0

Three factors were observed in the results:

The first factor is the water consumption in each building. The Department of Civil Engineering and the Department of Architecture and Engineering Projects buildings presented a much lower consumption compared to the other buildings. Both buildings also obtained the highest potential for potable water savings. All other buildings presented water consumption of the same order of magnitude with different distributions throughout the year, which resulted in different potentials for potable water savings for each city. It should be noted that the harvesting area in these buildings was not proportional to water consumption, and therefore buildings with smaller water consumption showed greater availability of rainwater.

The second factor is the rainfall pattern. The cities of Belo Horizonte and Brasília had a distinction between the rainfall volume in the dry period, which occurred in winter, and in the rainy period, which occurred in summer. This characteristic can be seen by analysing the standard deviation of the monthly average rainfall, which is, respectively, 96.12 and 113.15 mm/month (as shown in Table 4). For both cities, the monthly average rainfall in June, July and August did not exceed 20 mm/month, while in November, December and January it was over 200 mm/month. The cities of São Paulo, Manaus and Recife also did not show consistency in the rainfall pattern, with standard deviations equal to 84.71, 100.31 and 124.55, respectively. Finally, the cities in the south, that is, Florianópolis, Curitiba and Porto Alegre, showed low variation in the monthly average rainfall; the standard deviations were much lower than in the other cities, that is, 39.79, 33.49 and 16.73, respectively.

The third factor is the annual rainfall. The cities of Manaus and Recife have the highest annual rainfall, that is, 2287 and 2230 m^3/year, respectively. Both cities have considerably higher rainfall than other cities, which varied between 1454 and 1789 m^3/year. Thus, even if they have a variation in the monthly rainfall pattern, Recife and Manaus showed the greatest potential for potable water savings in some of the combinations between building and rainwater demand.

By combining these three factors, one can explain the results obtained. Low consumption buildings, such as the Department of Architecture and Engineering Projects, obtained the best results in all combinations of city and rainwater demand. Within the cities, the best results were obtained for Florianópolis, Porto Alegre and Curitiba due to low variation in rainfall. High consumption buildings, such as the Technology Centre, showed the best results in the cities with higher rainfall, that is, Manaus, Recife and Florianópolis. It can also be observed that Florianópolis presented the best result for low water consumption buildings and the third-best for high consumption buildings, as it has high annual average rainfall and low variation between months.

Differences in the water consumption pattern between buildings also influenced the results. As an example, the Technology Centre presented the best results in Recife and the

University Library presented the best results in Manaus. The difference in the results occurred as rainfall and water consumption distribution are different in both buildings and cities.

One also assessed how different rainwater demands influenced the results obtained for each building. In order not to extend the analysis of the results too much, the average potential for potable water savings for all cities was used. Table S1 in the Supplementary Materials shows the potential for potable water savings for each building and the rainwater demand. A linear regression was performed and the slope was calculated to assess the impact of the rainwater demand on the potable water savings potential. The linear regression slope was higher for the low water consumption buildings; therefore the rainwater demand has a greater impact on the potable water savings potential of low water consumption buildings. Although this impact is lower in high water consumption buildings, rainwater harvesting in such buildings can lead to significant monetary savings.

3.2. Hydrologic/hydraulic Design

The hydrologic/hydraulic design was performed using the method proposed by Hammes et al. [20], with the author's simplification for the specific output flow. Rainfall data were assessed for the last 15 years using data from BDMEP, based on Geraldi and Ghisi [52]. IDF curve data were obtained from published works that show local coefficients based on a locally measured rainfall database, as shown in Table 3. Table 6 shows the rainfall intensity, the number of rainfall events above the design rainfall and the extreme rainfall observed in the BDMEP data.

Table 6. Intensity-Duration-Frequency and hydraulic data for each city.

City	Design Rainfall Intensity (mm/h)	Number of Days with Rainfall Greater Than the Design Rainfall (days)	Highest Rainfall in a Day (mm)
Manaus	66.4	53	142.00
Recife	63.3	82	149.70
Brasília	58.6	35	110.70
Belo Horizonte	61.9	46	156.30
São Paulo	54.4	65	140.40
Curitiba	64.9	25	128.20
Florianópolis	102.9	12	253.00
Porto Alegre	47.4	76	149.60

R values equal to 1.50, 1.75 and 2.00 were used. They were obtained from sketches of the parking lots for each building. Table 7 shows the areas and the R values obtained from the sketches. Figure 9 shows the results obtained for the design of the reservoir course using the method of Hammes et al. The reservoir course thickness varied between 170 and 493 mm, depending on the city and building.

Table 7. Pavement areas and R-values.

Building	Permeable Area (m^2)	Impermeable Area (m^2)	Total Area (m^2)	R
Department of Architecture and Engineering Projects	875	875	1750	2.00
Department of Civil Engineering	800	800	1600	2.00
University Library	1575	1575	3150	2.00
Technology Centre	2750	2750	5500	2.00
University Administration Building	1100	550	1650	1.50
Department of Architecture and Urbanism	1160	870	2030	1.75

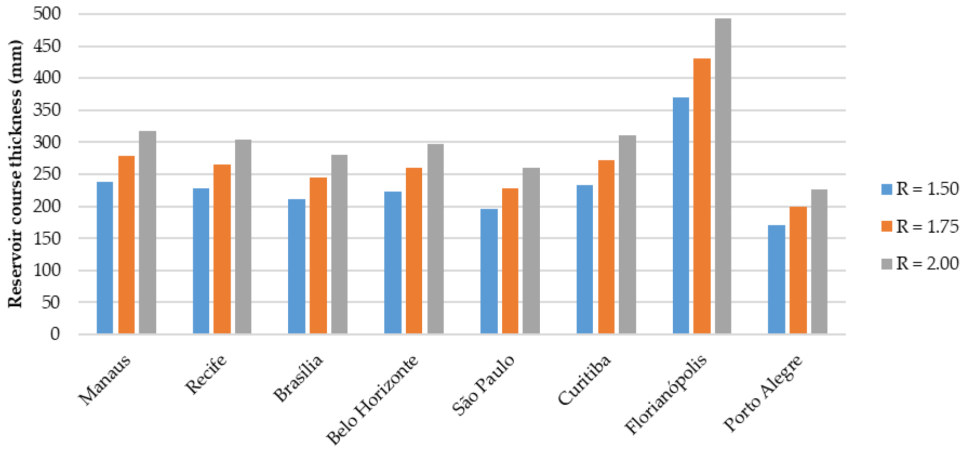

Figure 9. Hydrologic/hydraulic design thickness.

3.3. Structural Design

Structural design using the AASHTO method [26] was performed in a routine written in GNU Octave, while the ABCP method [27] was assessed using an abacus. Parameters used in the methods are shown in Table 8.

Table 8. Structural design parameters.

Parameters		Value
Pavers	Thickness	110 mm
	Structural coefficient	0.3 (dimensionless)
Choker course	Thickness	30 mm
	Structural coefficient	0.11 (dimensionless)
Reservoir course	Structural coefficient	0.08 (dimensionless)
	Drainage coefficient	0.4/0.6/0.8/1.0/1.2
Traffic	(80 kN axle) ESALs	100,000 (ESALs)
Subgrade	CBR (%)	5 (%) [1]
Method considerations	Zr [2]	−0.385 (dimensionless)
	So [3]	0.48 (dimensionless)
	ΔPSI [4]	2.2 (dimensionless)

[1] In order to plot Figure 10, values of CBR ranged between 1% and 20%, but 5% was used for the design. [2] Parameter is related to data reliability. It takes into consideration the type of pavement designed. [3] Statistical parameter related to standard deviation. It varies according to the type of pavement designed. [4] A dimensionless parameter used to consider the acceptance level of the pavement.

The number of ESALs was chosen based on light traffic, defined according to PMSP [27], which has design traffic of 100,000 ESALs. CBR of the subgrade was chosen to be 5%, according to the soil profile at the site, which presented very weak structural support capacity with low Standard Penetration Test (SPT) values. Thus, a choice was made to replace the material of the subgrade with soil with a bearing capacity equal to the minimum recommended for permeable pavements [51]. It is also worth mentioning that the AASHTO method uses the resilient modulus and not the CBR value, and thus a correlation was used to calculate the required thickness, according to Equation (8). In an executive project, it is necessary to find out the real resilient module of the layers materials. Figure 10 shows the variable results according to the CBR of the sub-bed and drainage coefficient.

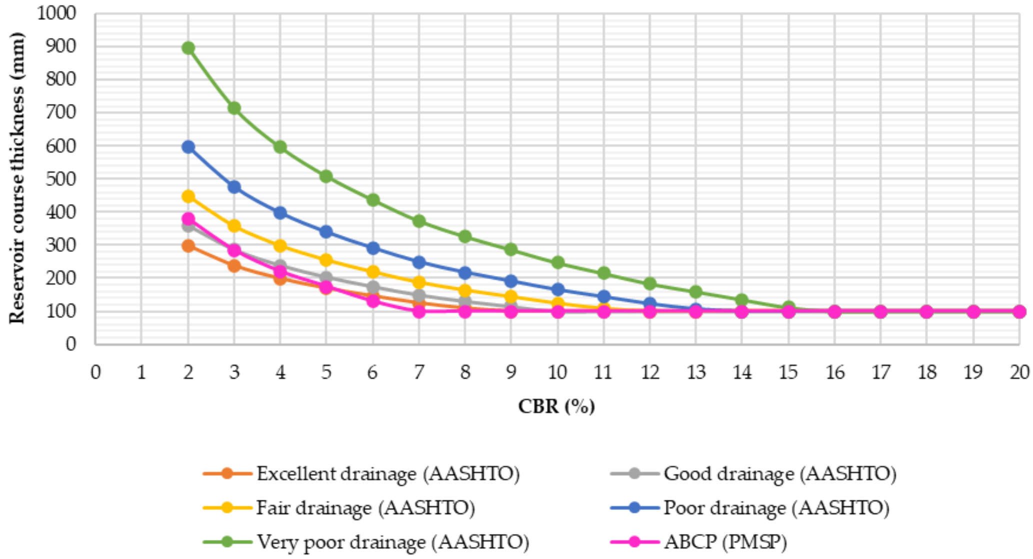

Figure 10. Structural design thickness.

The ABCP method resulted in a good estimation of the pavement thickness, presenting results similar to those of AASHTO for good and excellent drainage. However, in cases where the accumulation of rainwater for longer periods in the reservoir course is desired, the method becomes inefficient as it does not consider the drainage period. For CBR between 6% and 8%, the ABCP method led to results lower than those from AASHTO with excellent drainage and may represent insufficient thickness for the layer. It is also interesting to analyse the fact that, for CBR above 16%, regardless of the quality of drainage, all structural design is minimal.

The system was defined to be of fast storage type, that is, it does not maintain the rainwater for long periods. Thus, it was considered that the pavement should present good drainage, which indicates a thickness of 20.3 cm according to the AASHTO method and 17.5 cm according to the ABCP method. We chose a thickness equal to 21.0 cm in order to address the design of the AASHTO method.

3.4. Model Validation

The pavement was then modelled using the Permeable Design Pro computer programme. Two criteria are analysed through the design method of the programme, that is, structural and hydrologic/hydraulic requirements. The structural method is the same as that used in our study, that is, the AASHTO method. The drainage considered in the programme is good drainage, which corresponds to the outflow of water from the reservoir course in up to one day. Thus, the thickness obtained using the AASHTO method, 20.3 cm, did not differ from the result obtained from the Permeable Design Pro, that is, 20.5 cm. The final design thickness remained equal to 21.0 cm.

The hydrologic/hydraulic design method used in the programme is more precise than the method of Hammes et al. [20], requesting additional data. The programme creates a water balance on an hourly basis. In order to obtain the water balance, it uses the permeability of the pavement layers, drainage system parameters, pavement geometry and daily rainfall distribution.

Layer permeabilities were based on the programme standard figures for the choker course and reservoir course materials [51] and on Ghisi et al. for the paver layer [28]. Drainage data were defined according to the recommendations of permeable pavement manuals [47,49]. The pavement geometry was obtained through the parking lot sketches obtained through Google Earth Pro photos [31]; the streets were considered an impermeable area and the parking lots as a permeable area. Finally, the daily rainfall distribution was defined as the NRCS type III rainfall, because, among the options available in the programme, it presents the highest rainfall concentration, that is, it is the critical model. For each city, we adopted the rainfall curve with the intensities obtained from the IDF equations. Table 9 shows the parameters used in the Permeable Design Pro computer programme (ICPI, 2019).

Table 9. Hydrologic/hydraulic design parameters.

Parameter		Figure Considered
Pavers	Permeability (mm/s)	1.972
Choker course	Permeability (mm/s)	0.011
Reservoir course	Permeability (mm/s)	1.014
Subgrade	Permeability (mm/s)	0.000 (impermeable)
Drainage conditions	Daily rainfall distribution	Type III - NRCS
	Drainage area [1]	Variable
	Distance between adjacent drains [2]	6 m
	Drain diameter	10.0 cm
	Drain slope	0.5 %
	Drain roughness coefficient	0.012
	System's initial water volume	0.0 m^3
	Maximum water height in the reservoir course	100.0%

[1] Variable according to the building and its parking lot. For each parking lot, a sketch was made and the maximum drainage area that a single drain drains was assessed in order to size the drain; [2] The recommendation of the TSM permeable pavement manual [47] was taken into account.

In conclusion, 48 output reports were obtained, one for each combination of city and building. For the 48 combinations, the hydrologic/hydraulic design resulted in a reservoir course thickness smaller than that obtained in the structural design. Figures 11–14 show, as an example, the results obtained for the critical case, which occurred at the Technology Centre parking lot in Florianópolis.

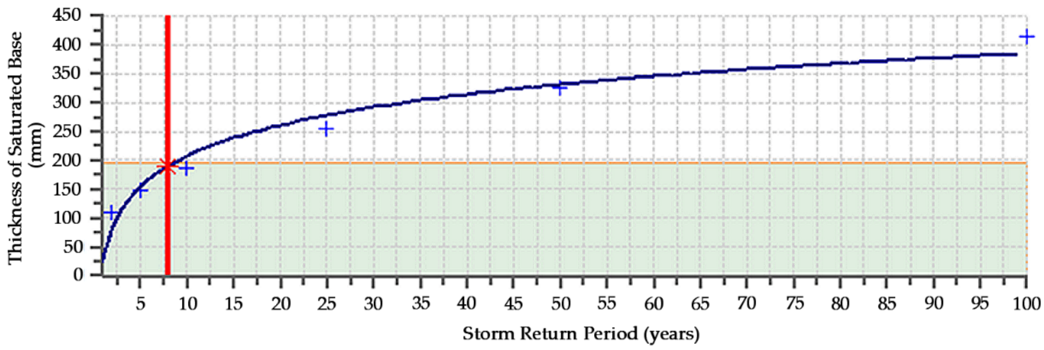

Figure 11. Thickness of saturated base (reservoir course) for the Technology Centre in Florianópolis.

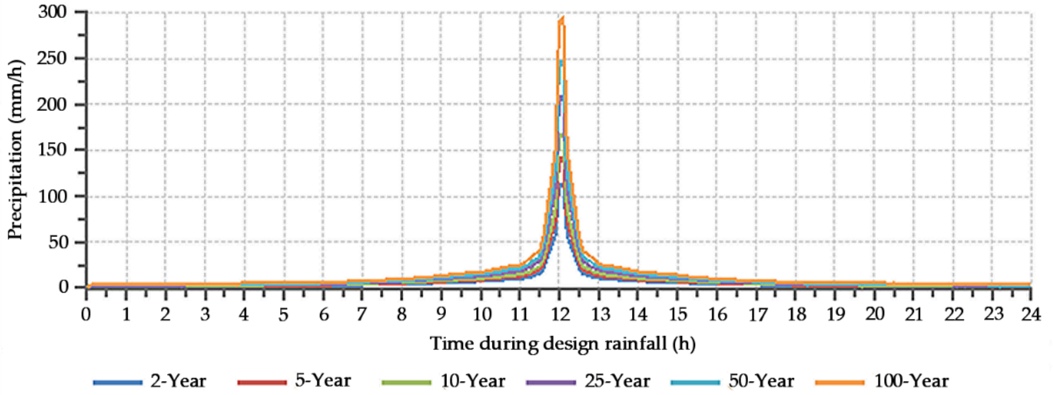

Figure 12. Precipitation considered in the model for the Technology Centre in Florianópolis.

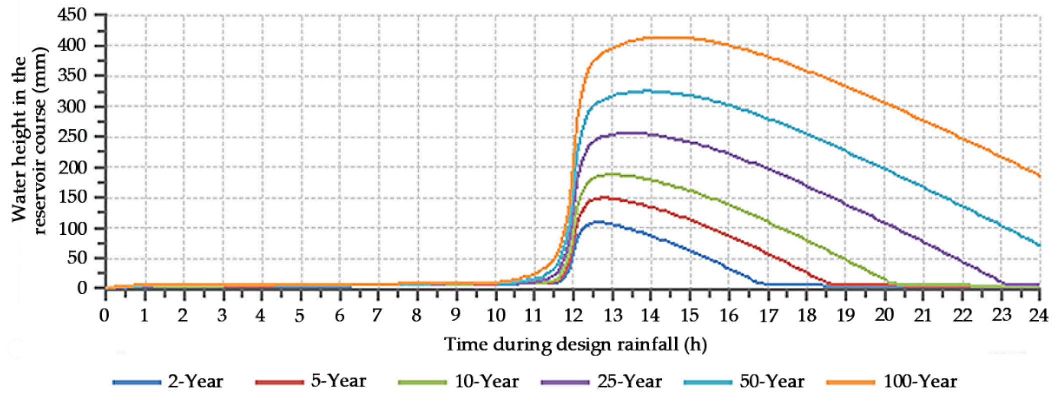

Figure 13. Water height in the reservoir course for the Technology Centre in Florianópolis.

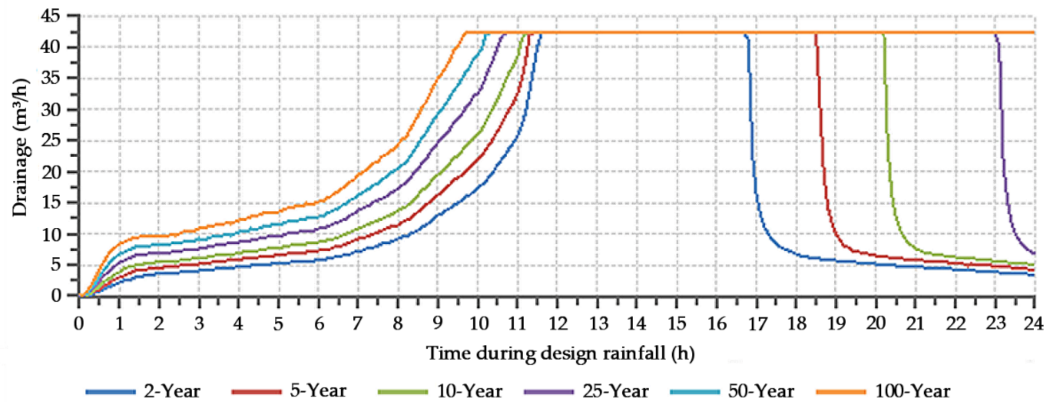

Figure 14. Drainage in the system for Technology Centre in Florianópolis.

The simplification used by Hammes et al. [20] was much in favour of safety, with a specific output flow much lower than the actual drain capacities. The divergence happens because the simplified model only uses one drain to collect all the branches of the drainage, without distinction among the branches that reach the rainwater tank.

4. Conclusions

In this work, an analysis of three aspects of permeable pavements was performed to improve knowledge about the technique. The first aspect was the evaluation of the potential for potable water savings as a result of stormwater harvesting. For this purpose, analyses were performed on the rainfall pattern of eight Brazilian cities and the consumption of six university buildings. The potential for potable water savings ranged from 18.48% to 82.81%. Such disparity in results is due to both large differences in water consumption patterns and differences in rainfall patterns. The city of Florianópolis presented the best results in terms of potable water savings potential overall, as it has a fairly constant rainfall distribution pattern and a high annual rainfall.

The second aspect verified was the structural design. For this, a GNU Octave code was written for the AASHTO method. The thicknesses according to the ABCP structural design method were also assessed. The results were validated through those obtained from the Permeable Design Pro programme, which also uses the AASHTO methodology for the structural design of permeable pavements.

There was little variation among the structural results of the ABCP method, the AASHTO code and the Permeable Design Pro, especially for the CBR of 5%. It should be noted that the ABCP method does not indicate the use of a choker course and does not consider drainage conditions, which may modify the result in other system settings. The absence of more parameters makes it less exact for the evaluation of permeable pavement systems with stormwater harvesting purposes.

The results of the hydrologic/hydraulic design using Permeable Design Pro diverged greatly from the values found using the method of Hammes et al. The main difference is that the programme considers an hourly water balance, requesting drainage specifications. The programme specific output flow was higher than the output flow obtained via the simplification that Hammes et al. considered. The difference obtained in drainage resulted in smaller reservoir course thicknesses.

It can be concluded that the results shown herein are examples of how a permeable pavement system can save potable water in buildings. It is believed that, for public universities, the system has a great potential for reducing the water bill costs and relieving the urban drainage systems.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13141896/s1, Figure S1: Rainwater harvesting schematic with water flows, Figure S2: Permeable and impermeable areas of the parking lot in the Technology Centre, Table S1: Potential for potable water savings and rainwater demand influence in the potential for potable water savings, Figure S3: Average, minimum and maximum monthly rainfall in the city of Florianópolis over 2003–2017, Figure S4: Average, minimum and maximum monthly rainfall in the city of Manaus over 2003–2017, Figure S5: Average, minimum and maximum monthly rainfall in the city of São Paulo over 2003–2017, Figure S6: Average, minimum and maximum monthly rainfall in the city of Recife over 2003–2017, Figure S7: Average, minimum and maximum monthly rainfall in the city of Curitiba over 2003–2017, Figure S8: Average, minimum and maximum monthly rainfall in the city of Belo Horizonte over 2003–2017, Figure S9: Water consumption for the buildings over 2013–2018, Figure S10: Daily water consumption in the Department of Architecture and Engineering Projects considered in the simulation, Figure S11: Daily water consumption in the Civil Engineering Building considered in the simulation, Figure S12: Daily water consumption in the University Library considered in the simulation, Figure S13: Daily water consumption in the University Administration Building considered in the simulation, Figure S14: Daily water consumption in the architecture and urbanism building considered in the simulation, Figure S15: Potential for potable water savings for the six buildings located in São Paulo, Figure S16: Potential for potable water savings for the six buildings located in Curitiba, Figure S17: Potential for potable water savings for the six buildings located in Brasília, Figure S18: Potential for potable water savings for the six buildings located in Belo Horizonte, Figure S19: Potential for potable water savings for the six buildings located in Manaus, Figure S20: Potential for potable water savings for the six buildings located in Recife, Figure S21: Potential for potable water savings for the six buildings located in Porto Alegre.

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Abbreviations

The following abbreviations are used in this manuscript:

IPCC	Intergovernmental Panel on Climate Change
SUDS	Sustainable Urban Drainage Systems
LID	Low Impact Development
LCA	Life Cycle Assessment
IDF	Intensity-Duration-Frequency
AASHTO	American Association of State Highway and Transportation Officials
ABCP	Brazilian Association of Portland Cement
UFSC	Federal University of Santa Catarina
BDMEP	Meteorological Database for Teaching and Research
ESAL	Equivalent Single Axle Load
CBR	California Bearing Ratio
ICPI	Interlocking Concrete Pavement Institute
SPT	Standard Penetration Test

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