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Financial Feasibility of Harvesting Rainwater from Permeable Pavements: A Case Study in a City Square

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Abstract: The objective of this study was to carry out the financial feasibility analysis of harvesting rainwater from permeable pavements in a city square. A case study was carried out in a square close to the beach in the city of Florianópolis, Brazil. Questionnaires were applied to pedestrians who circulate within the area. The square is to be implemented to promote sustainability and improve the user's quality of life. From the rainfall data and the average daily water demand for irrigation of the square vegetation, the volume of rainwater to be harvested from the permeable pavement was calculated. The rainwater demand was estimated as 662 L/day. The implementation and operation costs of the pavement and irrigation systems were evaluated. The potential for potable water savings was 89.8%. The payback period was estimated as 347 months. This study showed that rainwater collected from permeable pavements is financially feasible and represents a promising technique.

Keywords: city square; permeable pavements; potable water savings; rainwater; financial analysis

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1. Introduction

Water scarcity is a relevant issue and a worldwide concern, and the United Nations predict a world water deficit of 40% by 2030 [1]. According to Kummu et al. [2], water consumption per capita throughout the 20th century showed a slight and irregular increase. On the other hand, the increase of water scarcity is primarily justified by the effects of the spatial distribution of population growth concerning water resources [2]. Despite Brazil being a country with many freshwater sources and abundant rainfall in most regions [3,4], there has been a sensible reduction in water levels in catchment systems since 2014, especially in cities like São Paulo [5], Florianópolis [6] and Brasília [7]. In addition, due to the reduction of permeable surfaces and insufficient urban drainage systems capacity promoted by accelerated urbanisation, some cities worldwide have been facing floods.

Water management is fundamental to guaranteeing sustainable harmony between the population and the natural environment. Thus, alleviating the demand for the urban drainage system is a collaborative attitude with the society. Studies on the use of alternative sources such as rainwater and reuse of water can generate several benefits such as irrigation of plants and green areas, supply of artificial lakes, fountains, and toilet flushing. The *Fukuoka* Dome baseball stadium in Japan is equipped with a rainwater catchment system designed to irrigate the turf and flush toilets. The capacity of the rainwater tanks is 1800 m^3 [8]. In Brazil, in the *Mineirão* football stadium in Minas Gerais state, rainwater is collected from the roof and the permeable pavement (located in the surroundings of the stadium), whose reservoir is a 6000 m^3 retention lake located around the stadium [9].

Public squares are places where locals meet in most municipalities. Historically, squares are used for the following: motivating the movement of people, benefiting the exchange of goods and information, promoting performances, demonstrations or public meetings or simply contemplation [10]. In city squares, urban quality can coexist with life in public spaces [11].

On the other hand, with the accelerated development of cities, population increase and real estate speculation, tree-lined city squares have been replaced with buildings and parking lots [11,12]. Currently, depending on the level of urbanisation in a city, squares represent an oasis in the urban areas. In order to provide well-being to the user of public spaces, furniture and urban equipment such as benches, lighting, vegetation and shading are essential [13]. However, squares are limited by the urbanisation level of cities, whose applicability of sustainability criteria to the project has become a complex task [14].

Environmentally, city squares play an essential role as vegetation promotes microclimates [15]. Municipalities with more green areas have environmental benefits such as reduced heat waves, reduced air pollution and the existence of larger permeable areas. In this way, the environmental impact study is essential during the design in order to ensure that the environmental dimension is considered [16]. Good air quality and pleasant temperatures will make the square a suitable place and more used by people. Thus, the environmental and social solutions are directly connected [17].

There are technologies, inputs and certification systems for the environmental performance of projects and constructions that make it possible to generate savings based on sustainability. One can cite sustainable certification systems such as BREEAM in the United Kingdom, LEED in the United States and AQUA in Brazil [18].

One of the sustainable technologies is the use of rainwater in order to facilitate the supply and reduce the demand for drinking water. Although the implementation of rainwater use systems is not always financially profitable [19,20], the environmental benefits provided by such systems should not be neglected. Studies in the residential sector show that there are places with a high potential for saving potable water through rainwater usage [21,22]. In Southern Brazil, it was found that it is possible to save up to 44.8% of potable water by using rainwater [21]. In the United Kingdom, implementing a rainwater harvesting system in residential and commercial buildings in a developing community could reduce the demand for potable water by 62% to 71% [22].

Considering the roof areas of two cities in Northeastern Brazil, Gomes et al. [23] concluded that it would be possible to save 44.4% to 51.1% of potable water by using rainwater. Rainwater usage may not only increase water savings in cities, but also contribute to the reduction of runoff peaks. Antunes et al. [24] evaluated the potential for potable water savings through rainwater harvesting in paved areas of Florianópolis (Southern Brazil). The authors found that the potential for potable water savings can reach 75.5%. Vaz et al. [25] evaluated the potential for potable water savings through rainwater harvesting in parking areas in Southern Brazil. According to Vaz et al. [25], such a potential may vary from 18.4% to 84.8%, depending on the climate considered, the potable water demand and the demand for non-potable purposes in the building.

Kim and Song [26] assessed several benefits of green infrastructure applied to communities. Among the five most used sustainable techniques in projects, there are the use of permeable pavements and the use of rainwater. According to the research, in addition to financial savings, applying sustainable techniques has other benefits, such as educational opportunities, improved built environment, flow control and enhanced environmental soundness.

As for drainage, public squares have an adequate capacity to reduce urban flooding and its consequences [27]. Additionally, it is essential to seek strategies to use rainwater to reduce water consumption, especially with the irrigation of plants and cleaning the square [28].

This study aims to assess the financial feasibility of implementing a system for using rainwater collected from permeable pavements in a city square located in Florianópolis, Southern Brazil. The specific objectives of this study are as follows: proposing a basic project for a square which promotes the life quality of the local community; quantifying the water demand needed to irrigate the square's vegetation; assessing the potential for rainwater harvesting by using permeable pavements in part of the square's area; and finally, estimating the ideal rainwater storage tank capacity. The construction of a sustainable square provided with a rainwater harvesting system, in addition to establishing the involvement of the community and nature, enables the creation of sustainable living spaces with benefits such as less pollution, minor use of natural resources, promotion of social interaction, education and awareness of sustainable practices, as well as energy savings.

2. Materials and Methods

The methodology comprises four phases as shown in Figure 1. The first phase corresponds to collecting rainfall data from the region where the project is implemented. The second phase corresponds to the square's architectural and landscape design: the definition of the route for pedestrians crossing on a permeable pavement; the definition of leisure spaces, lighting and landscaping area. The third phase corresponds to some project parameters' definitions, which are necessary for the rainwater harvesting system's simulation (such as the demand for water needed for irrigation, for example), as well as the survey of the materials and labour costs for the system deployment. Finally, the simulation and the financial analysis of the system are conducted.

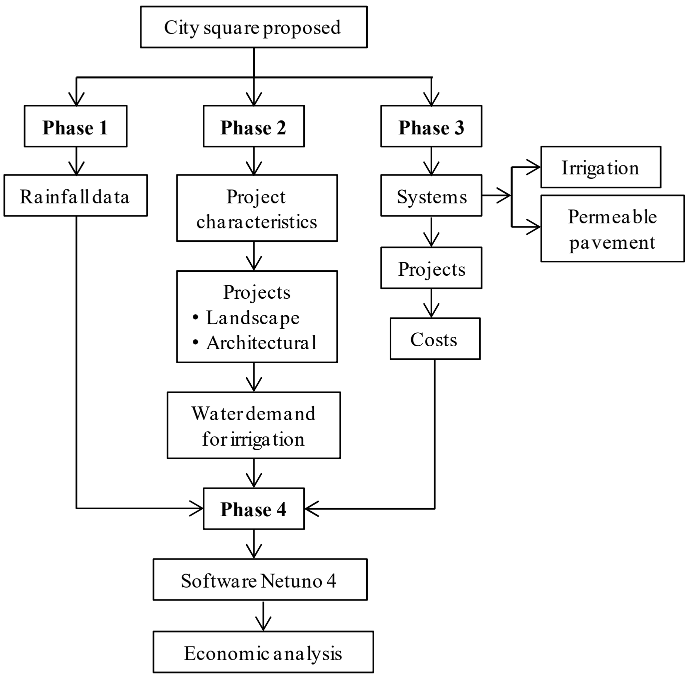


Figure 1. Flowchart of the methodology.

2.1. Rainfall Data

In phase 1, rainfall data from the two stations located in Florianópolis were collected. Such stations are close to the study site, and the data were obtained from EPAGRI [29]. The data comprised daily rainfall records from 8 January 1996 to 23 July 2021. Then, the data were processed and used as inputs into the Netuno computer programme version 4.

2.2. The Square

For the square implementation, an open plan area measuring 4700 m^2 was chosen, located near the beach, at the geographic coordinates 27°39′55.28′′ S and 48°28′40.04′′ W, in the Campeche district, Florianópolis city, in Santa Catarina state, Brazil (Figures 2 and 3). In the square's architectural and landscape design stage, a financial feasibility study was performed following the master plan of Florianópolis.

The walking flow, already commonly used by pedestrians, was chosen to implement the square, covering its borders up to the point closest to the beach access. Still, in order to bring users closer to nature, aspects related to size, shape, landscaping, social interest, terrain slope, plant species, prevailing winds and shading were analysed.

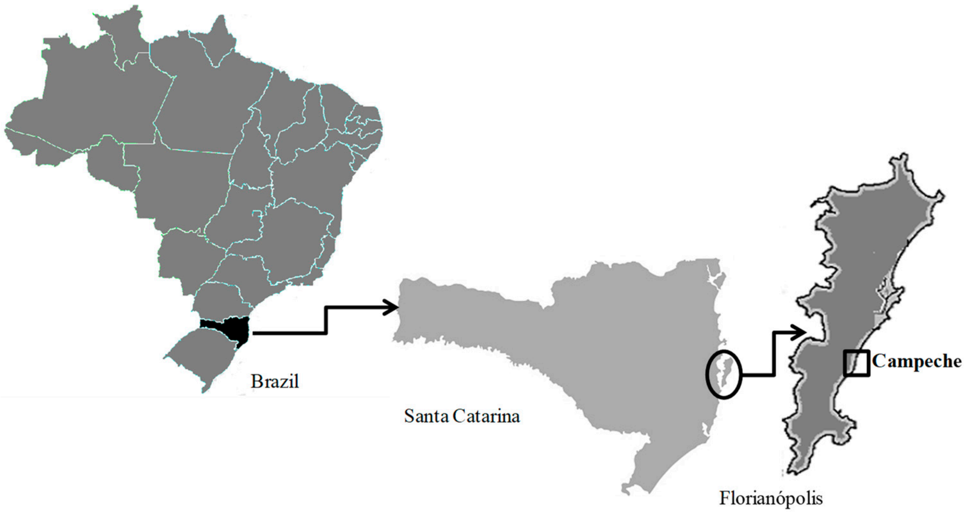


Figure 2. Location of the case study.

Figure 3. Area chosen for the square (based on [30]).

Through a questionnaire, the population was asked to contribute to the square's project. A selection criterion for choosing participants to contribute to the project was that pedestrians were residents or regulars of the Campeche neighbourhood. People were asked about the areas they consider essential in a public square, users' opinions regarding rainwater usage and implementing a public square in the neighbourhood and knowledge about permeable pavements. The participants' opinions were collected using an electronic questionnaire which provided an overview (images were shown) of the proposal for the square's design. Table 1 shows the questions and participants' response possibilities (for open-ended answers).

The rainwater collected in the square was used for irrigation. In the landscaping project, native plants were used. To quantify the rainwater demand for irrigation, the evapotranspiration was calculated by using Equation (1) [31]:

$$ET_S = K_S \times ET_0 \quad (1)$$

where ET_S is the vegetation surface evapotranspiration (mm/day); K_S is the vegetation surface coefficient (dimensionless); ET_0 is the reference evapotranspiration (mm/day).

The vegetation surface coefficient was estimated at 0.7, which was a result of the multiplication of three factors [30,31]: the species of plants considered (factor estimated at 0.5), the density of vegetation (factor estimated at 1.0) and the region's microclimate (factor estimated at 1.4). The reference evapotranspiration was assumed as 2.8 mm/day, according to a research study [31,32] conducted near the region and with similar characteristics to the Campeche district.

Table 1. Questions and possible answers of the questionnaire applied in the study.

Questions	Possible Answers
What do you think is essential in a public square?	(a) Benches (social life area); (b) pet area; (c) public vegetable garden; (d) lighting; (e) children's playground; (f) sports court; (g) recreation area; (h) area for events; (i) skate lane; (j) snack bars; (k) shower; (l) public restrooms; (m) bike rack; (n) space for fairs.
Do you think rainwater harvesting solutions are interesting?	Yes or No
Do you know the technique of rainwater harvesting by using permeable pavements?	Yes or No
Do you agree that sustainable examples coming from the city council would help to change the population's thinking about the environment?	Yes or No
Would you use a public vegetable garden?	Yes or No
Would you seek to know more about solutions for rainwater harvesting when having contact with a square provided with such a system?	Yes or No
Do you believe that a public square and the type of architectural design suggested would promote social well-being and better interaction between people?	Yes or No
Do you believe that the implementation of the public square using the suggested architectural design would help even more in the real estate appreciation of the region?	Yes or No
Do you have any questions, comments or suggestions?	Not applicable (open answer)

2.3. Rainwater Harvesting System

The square's water use system was divided into two groups that operated together, as the irrigation system, responsible for distributing stored rainwater, and the permeable pavement, whose function was to collect and store rainwater.

The definition of the drainage pavement model used in this study was based on comparisons of results obtained by previous studies [25,32,33]. Figure 4 shows the adopted structure, i.e., a surface layer with permeable interlocked Portland cement blocks, a bedding layer (fine aggregates with 4.8 mm in diameter), a choker course (coarse aggregate with 19.0 mm in diameter), a filter course (fine aggregate with 4.8 mm in diameter), a filter blanket (coarse aggregates with 9.5 mm in diameter) and a reservoir course (coarse aggregates with 37.5 mm in diameter). The corrugated drain diameter was 100 mm, and it was installed on a draining bedding (coarse aggregate with 50 mm in diameter).

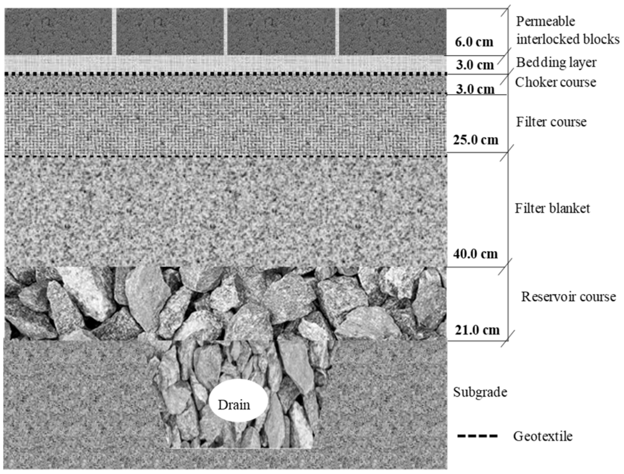


Figure 4. Cross-section of the permeable pavement structure (based on [32,33]).

For the irrigation system, information on the square's landscape layout project, the daily amount of water for irrigation, rainwater tank volume and location were needed. The equipment and materials used in the irrigation system were those available in the Brazilian market.

2.4. Computer Simulations

In phase 4, a simulation was carried out using the Netuno computer programme to define the necessary rainwater tank capacity and the potential for potable water savings. In addition, using Netuno, all the costs and parameters involved were determined to perform a financial analysis of the rainwater harvesting system.

3. Results and Discussion

3.1. Rainfall Analysis

Florianópolis presented a constant rainfall pattern, without monthly defined periods of dry or rainy weather. The period from May to August had the lowest mean rainfall in the city, which may require more water supply. The minimum, maximum and average monthly rainfall in Florianópolis, calculated using the historical series from 1996 to 2021, are shown in Figure 5.

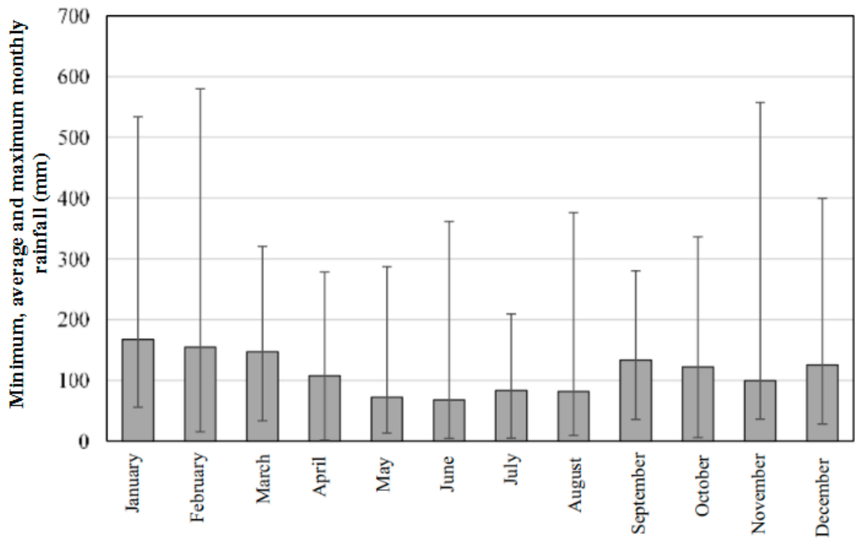


Figure 5. Minimum, maximum and average monthly rainfall in Florianópolis from 1996 to 2021 (based on [29]).

3.2. Architectural and Landscape Square Design

The population contributed to defining the primary purposes of the square. In total, 120 responses of 120 participants were collected from residents and regulars of the region planned for the square implementation. Through the questionnaire answers, it was possible to establish the basic needs. The results obtained from the questionnaire are shown in Figure 6. It can be seen that most of the population consider that a public square needs to have lighting, benches for social interaction, a pet area, a children's playground and a recreation area.

Regarding the sustainability questions, 97% of those interviewed agreed that the square would promote social well-being and a better relationship between people, and 96.3% said that the square would improve the region's real estate valuation. Moreover, 98% agreed that rainwater harvesting and vegetation irrigation solutions are important, but only 38% knew about harvesting rainwater and irrigation techniques.

In addition, according to the answers obtained, 88.9% of the interviewees declared that they would seek more information about rainwater harvesting when having contact with a square provided with such a system, and 99.1% attested that sustainable examples coming from the city council would help to promote environmental conservation.

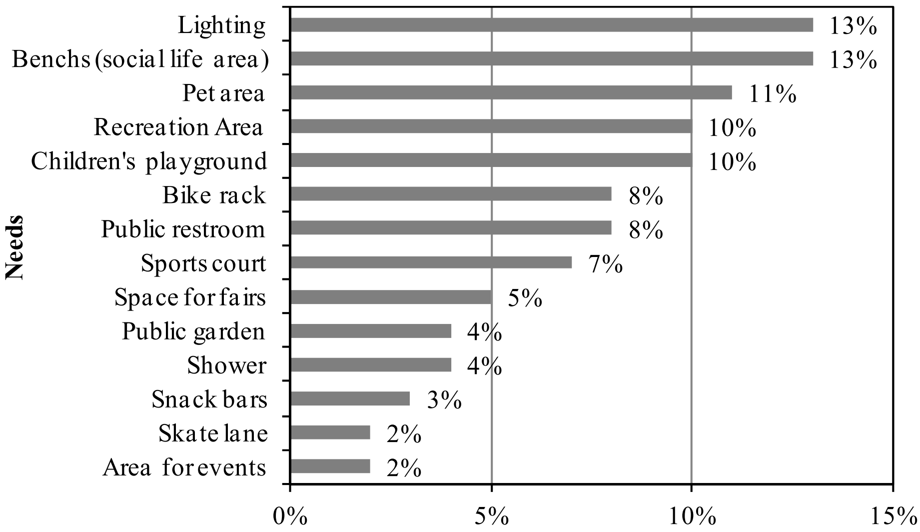
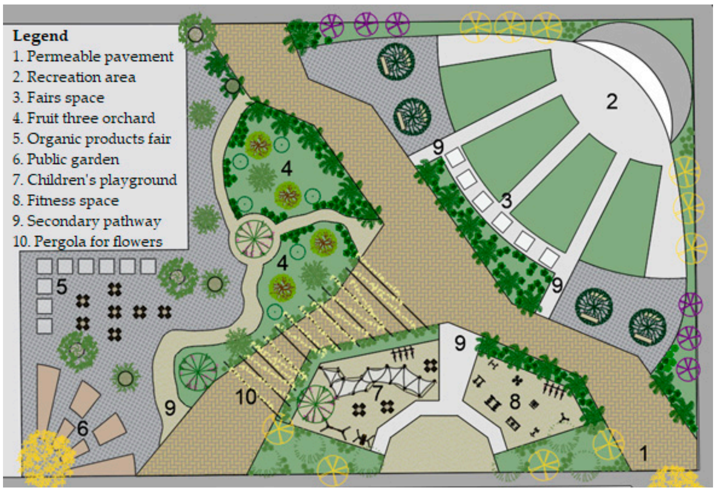


Figure 6. Results obtained by applying the questionnaire.

Considering the population interests related to the square implementation, the following spaces and activities were selected as shown in Figure 7a,b, in the plan and 3D views, respectively.



(**a**)

(**b**)

Figure 7. Public square design. (**a**) Plan view (scale: 1:1000). (**b**) 3D view.

The recreation area, children's playground and the fitness area were waterproof, totalling 1881 m^2. There is a five-metre-high acoustic shell for public entertainment events.

The landscaped part of the square to be irrigated was distributed in 500 m^2, using native plants from Florianópolis. The irrigation sprinklers distribution (Figure 8) was designed according to the specifications (manufacturer), considering the area where irrigation arrives. Thus, it was possible to define the design flow, system layout and electricity consumption.

Figure 8. Irrigation system.

The evapotranspiration calculated (1.96 mm/day) multiplied by the landscaping area (500 m^2) led to the total water demand for irrigation, i.e., 980 L/day, evenly distributed over the surface. However, such a demand would be valid for a scenario without rainfall. Once rainfall supplies the vegetation water demand on rainy days, eliminating irrigation needs, the actual water demand was estimated by assessing the historical rainfall series.

Afterwards, the difference between the precipitated volume and the total daily consumption in the square was calculated, estimating the amount of water to be provided by the rainwater harvesting system per day in the entire historical series. Firstly, among the daily precipitation data used in the simulation, the days which presented daily precipitation less than 1.96 mm were sought, since 980 L of water are needed for the irrigation of the vegetated area (500 m^2). It is known that the water volume supplied by the system depends on the design water flow, which based on the definition of the irrigation layout and the unit specification of the sprinklers (0.062 m^3/h) corresponds to 1.798 m^3/h. Figure 9 shows the monthly average amount of water, in litres per month, needed to supplement rainwater. The daily average of the total water demand supplied by the rainwater harvesting system was calculated, which resulted in 662 L/day.

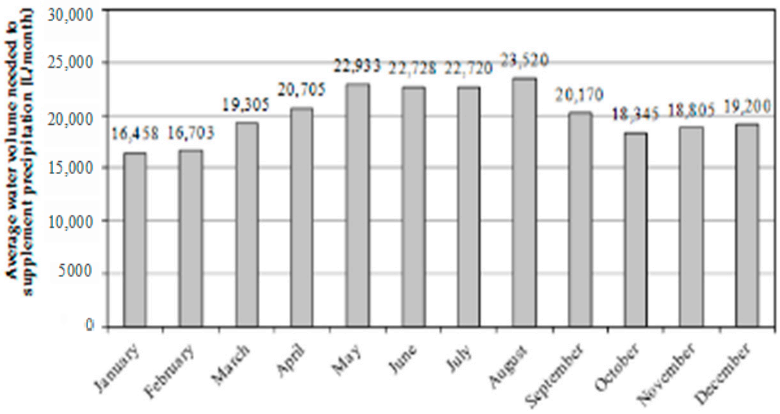


Figure 9. Monthly volume of water needed to complement rainfall.

3.3. Potential for Potable Water Savings

Based on the historical series of daily rainfall, the daily water consumption in the square was estimated using Netuno (Figure 9). However, due to the software's limitations, it was decided to use the system's average daily amount of water to meet the square's water requirement for fixed daily consumption. As a result, considering that the square's total average annual water consumption is 357.7 m^3, of which 116.1 m^3 is supplied through direct rainfall and the remaining 241.6 m^3 water is supplied by the rainwater system. Therefore, the square's total daily water demand for simulation purposes is 662 L/day. Table 2 shows the input data used in Netuno.

Table 2. Input data for the computer simulations.

Input Data	Value
Rainfall	Historical series
Start date	8 January 1996
First flush	0 mm
Catchment area	1000 m^2
Total water demand	662 L/day
Total demand replaced by rainwater	100%
Runoff coefficient	78.1%
Maximum capacity of the rainwater tank	60,000 L
Interval between rainwater tanks	5000 L

As for the other input data, it was considered that the catchment area represents the square permeable pavement (1000 m^2). As the rainwater harvesting system is entirely used for irrigation, the total water demand to be replaced with rainwater is 100%. The runoff coefficient of 78.1% was measured by [33]. Other inputs required for simulation are the maximum tank capacity and the interval between capacities. The tank capacities and their costs were obtained on the local market, and then, for simulation, the maximum volume of 60,000 litres and the interval at every 5000 litres were tested.

The simulation results (Figure 10) showed that even the highest simulated rainwater tank capacity would not completely meet the water demand needed for irrigation. For rainwater tanks with capacities greater than or equal to 10,000 litres, the potential for potable water savings remains almost constant. Therefore, it is not interesting to use a tank capacity greater than 10,000 litres. The cost of using rainwater tanks with higher capacities would not be justified by the slight increase in potable water savings that they would provide. Thus, a 10,000-litre tank was chosen, which resulted in a potable water saving potential equal to 89.8%.

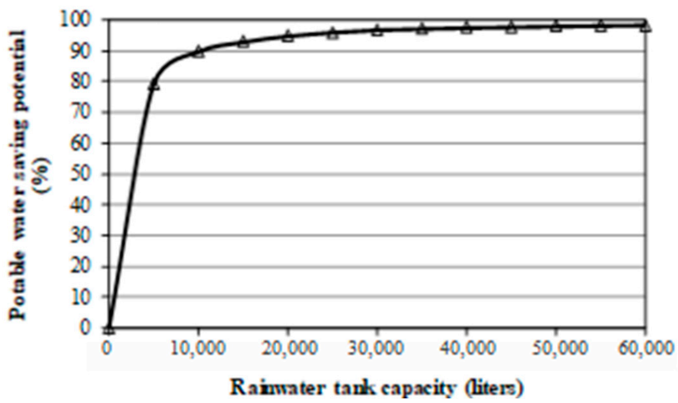


Figure 10. Potential for potable water savings as a function of the rainwater tank capacity.

Figure 11 shows the amount of rainwater supplied by the rainwater harvesting system, and Figure 12 shows the percentage of absolute demand supplied through the system. The results showed that August is the most critical month, since vegetation will need greater amounts of potable water to supplement rainwater. The January, April and September months had higher water supply from the rainwater harvesting system.

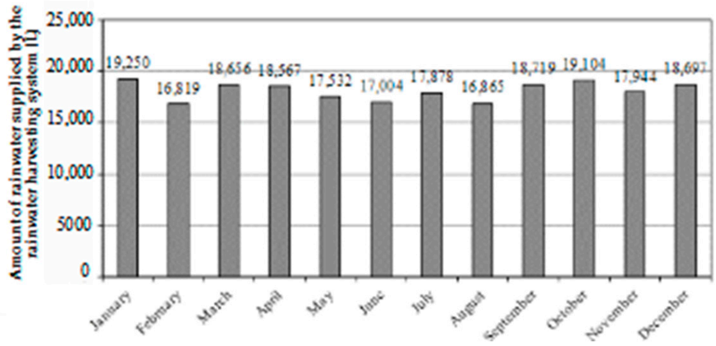


Figure 11. Monthly rainwater supplied by the rainwater harvesting system.

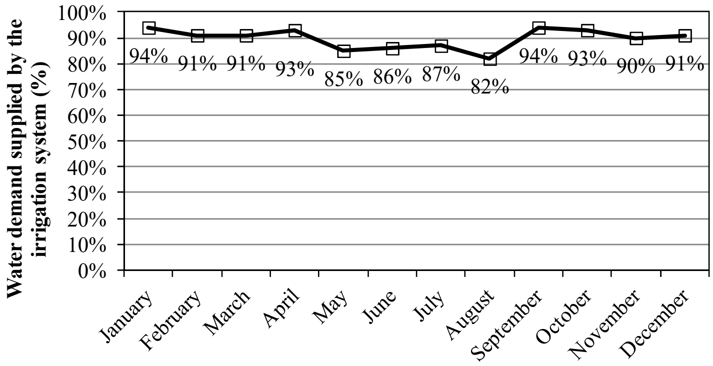


Figure 12. Percentage of the total demand supplied by the irrigation system.

3.4. Financial Analysis

First, the initial construction and operation and maintenance costs were defined, and the fees for potable water supplied by the water utility were considered. The financial analysis was performed using Netuno, whose input data are shown in Table 3.

Table 3. Input data for the financial analysis.

Parameter	Value
Water and sewage fees	Variable [a]
Electricity tariff	2.50/kWh
Brazilian taxes	9.25%
Inflation	0.72%
Rates and service adjustment periods	12 months
Analysis period	30 years
Minimum attractive rate of return	0.2% per month
System installation month	January
Construction costs	US$ [b] 7736
Rainwater tank cost	US$ [b] 1580
Pipes and drains cost	US$ [b] 910
Accessories cost	US$ [b] 11,142
Maintenance costs	US$ [b] 17.55/month
Electricity cost	US$ [b] 2.35/month

[a] US$ 11.5 for consumption between 1 and 10 m^3/month or US$ 53.5 for consumption higher than 11 m^3/month; [b] R$, Real, the Brazilian currency was converted to American dollars (US$) considering that 1.00 Real equals to US$ 5.70.

The net present value (NPV), the internal rate of return (IRR), and discounted payback methods were used. The NPV returned a positive value of US$ 1654, indicating that the investment is feasible. The IRR resulted in 0.47% per month, that is, higher than the minimum attractive rate of return, and therefore, it is possible to assure that the project is feasible. The discounted payback period was 347 months. Table 4 shows the financial analysis results.

Table 4. Financial analysis results.

Parameter	Result
Net present value (NPV)	US$ 1654
Internal rate of return (IRR)	0.47% month
Discounted payback	347 months

A payback period of 29 years is long, characterising the investment as of high risk. However, the financial benefit was evaluated only by the water savings from the utility, whose cost is lower compared to the cost of the initial investment.

In addition to the financial benefit from water savings, using permeable pavements and rainwater provides other more complex benefits to be monetarily quantified, such as reducing surface runoff in the urban environment and mitigating floods. Flooding reduction in cities, in turn, reduces the probability of infrastructure or personnel damage in cities [34]. A comprehensive analysis would be necessary to evaluate such benefits, as suggested by Teston et al. [35].

Therefore, taking into account sustainability and the promotion of improved quality of life for the population, it can be concluded that the investment is feasible. Figures 13–16 show some views of the square.

Figure 13. Main path on permeable pavement.

Figure 14. Vegetable garden.

Figure 15. Fitness space and rest areas.

Figure 16. Centre point of the square.

Permeable pavements can also be used to mitigate the urban heat island effect [36,37] and collect rainwater to be used in buildings as a means of saving drinking water [25,38,39], filter rainwater [33,40,41] and many other benefits. The environmental benefits of using permeable pavements have also been assessed [38,42].

In addition to the benefits generated by permeable pavements, the results obtained through questionnaires and other research [26,43,44] report on the importance of involving the population in the process of implementing sustainable systems. The importance of community involvement in implementing rainwater harvesting systems is also highlighted in the study conducted by Campisano et al. [45]. Using sustainable techniques in public spaces provides more opportunities for the population's environmental education. Implementing sustainable projects is a tool to make the population aware of preserving environmental resources and disseminating more sustainable solutions in the construction sector.

4. Conclusions

This paper assessed the financial feasibility of implementing a system for harvesting rainwater from permeable pavements in a city square. The study showed the importance of harvesting rainwater in social spaces.

The project was developed through architectural and landscape proposals for the square. The climatic conditions related to the rainfall series in the region were evaluated, and the water consumption required for irrigation of the square's vegetation was estimated.

Before proposing the project, the community's opinion was considered by applying a questionnaire. Such a tool was important, because it allowed the inclusion of friendly solutions for users, taking into account their habits and seeking to better integrate the surroundings into the square and the environment. The local life quality was sought by designing attractive proposals and creating a space for social interaction and the users' well-being, including sustainability.

The architectural and landscaping project proposals contemplated the primary needs of people obtained from the questionnaires' responses. By exploring the walking flow that was already naturally used by pedestrians, seeking to bring them closer to sustainable proposals and connecting the end of the square to the closest access to the beach, the proposal managed to relate the social and environmental dimensions. The system's adoption creates a milder microclimate in the region, produced by the conjunction between landscaping native plants of Florianópolis and the permeable pavement technique, generating comfort for the user and bringing the population closer to nature.

The rainfall analysis showed that the city has rain patterns well distributed during the year, without a period of high rain or drought. However, the historical series showed monthly rainfall variation, which showed differences in rainwater collection and, consequently, in the amount of water supplied to the vegetation. For the months with the lowest rainfall, a supplementation from potable water from the water utility should be provided.

Potable water savings potential simulations were performed using the Netuno computer programme. The daily rainwater demand for irrigation was estimated at 662 L/day, and the potential for potable water savings ranged between 79.3% and 98.4% per month, depending on the rainwater tank capacity to be used (from 5000 L to 60,000 L).

When assessing the potential for potable water savings due to rainwater usage for irrigation, an ideal rainwater tank volume corresponding to 10,000 L was achieved. Rainwater tanks with higher volumes increase potable water savings, but such an increase is relatively tiny concerning the increase in the tank capacity (a very large capacity would be necessary).

The financial analysis results showed that the investment is feasible. The IRR resulted in a value greater than the minimum attractive rate of return, the NPV was higher than zero, and the payback was lower than the analysis period. However, the payback resulted in a long period due to the return on capital being exclusively generated by the savings on the water bill, considered a relatively low value compared to the initial investment.

This study included analyses that harmonise the three dimensions of sustainability and promote significant benefits to the population and its interaction with the environment to achieve full sustainability successfully.

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