

Assessment of Potable Water Savings in Office Buildings Considering Embodied Energy

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Abstract The objective of this article is to assess the potential for potable water savings in office buildings located in Florianópolis, southern Brazil. The embodied energy of four alternatives to reduce potable water demand, i.e., rainwater harvesting, greywater reuse, dual-flush toilets and water-saving taps, was also assessed. The analyses took into account the potable water end-uses for ten buildings. The potential for potable water savings by using rainwater, as well as, the rainwater tank sizing were estimated using computer simulation. As for greywater reuse, it was considered that greywater from lavatory taps could be treated and reused to flush toilets. The potential for potable water savings by using water-saving plumbing fixtures was estimated by considering the replacement of toilets and taps. In order to estimate the embodied energy in the main components, each system was dimensioned and embodied energy indices were applied. The main result is that the potential for potable water savings by using dual-flush toilets ranges from 21.6 % to 57.4 %; by reusing greywater, it ranges from 6.8 % to 38.4 %; by using rainwater, it ranges from 6.1 % to 21.2 %; by using water-saving taps it ranges from 2.7 % to 15.4 %. However, by considering the embodied energy, the average for the ten buildings indicates that dual-flush toilets are the best choice as it is possible to obtain water savings of 5.50 m³/month per GJ of embodied energy, followed, respectively, by water-saving taps, greywater reuse and rainwater usage. The main conclusion is that the assessment of embodied energy should be considered when evaluating potable water savings in buildings as it helps to identify the best alternatives to save more water while causing less environmental impact.

Keywords Potable water savings · Water end-uses · Embodied energy · Office buildings

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1 Introduction

In order to ease environmental impacts, research on decreasing potable water consumption in buildings has been carried out worldwide. Rainwater harvesting to be used in residential, commercial and public buildings as well as in industries has been assessed by many researchers such as Gould 1999; Chilton et al. 2001; Coombes et al. 2000; Herrmann and Schmida 2000; Handia et al. 2003; Sautchúk 2004; Ghisi 2006; Ghisi et al. 2006; Aladenola and Adeboye 2010; Islam et al. 2010; Zhang et al. 2012; to quote just a few. Greywater reuse in buildings has also been assessed (Nolde 2000; Ghisi and Ferreira 2007; Ghisi and Oliveira 2007). More recently, some studies on water-saving plumbing fixtures have also been published (Uchida and Oliveira 2006; Hamzo and Barreto 2007; SABESP 2008; Yurdusev and Kumanlioglu 2008).

On the other hand, as an attempt to improve sustainability in buildings, studies about embodied energy in components and systems of buildings have been performed (Cole and Kernan 1996; Pullen 1999; Treloar et al. 1999; Winther and Hestnes 1999; Chen et al. 2001; Tavares 2006; Sartori and Hestnes 2007; Jiao et al. 2012). Also, in a wider sustainability evaluation framework than intended in this paper, there are studies that propose dynamic performance metrics to quantify sustainability and cost effectiveness of integrated urban water systems in order to inform policy, design and management decisions (Fagan et al. 2010). Such dynamic systems integrate the subsystems of the water cycle, i.e., water supply, urban water consumers, industrial water consumers, agricultural water consumers, storm-water generation and treatment, and sewerage and wastewater treatment. On the other hand, Mo et al. (2010) assessed embodied energy in drinking water supply systems. However, there have been no specific studies on the environmental impact of using rainwater, reusing greywater and replacing old plumbing fixtures with water-saving fixtures in buildings when embodied energy and potable water savings are taken into account as a single indicator.

Therefore, this article contributes to improving the knowledge by assessing the potential for potable water savings in office buildings by using rainwater, reusing greywater and replacing conventional plumbing fixtures with water-saving ones, and by investigating the embodied energy of such alternatives. An indicator that relates potable water savings and embodied energy to identify the alternatives that cause less environmental impact and improve sustainability in buildings is also proposed.

2 Objectives

The objectives of this article are to estimate the potential for potable water savings by using rainwater, reusing greywater and installing water-saving plumbing fixtures in office buildings located in Florianópolis, southern Brazil; and assess the environmental impact by estimating the embodied energy of such alternatives to reduce potable water consumption.

3 Methodology

3.1 Rainwater Harvesting

In order to estimate the potential for potable water savings by using rainwater, rainwater was considered for toilet flushing only. As this is a theoretical analysis, rainwater treatment was not taken into account. The Netuno computer programme (Ghisi and Tavares 2008) was

used to assess such potential for potable water savings. Information on the algorithm of this programme can be found in Ghisi (2010); and information on its validation can be found in Rocha (2009).

Input data to Netuno are daily rainfall, catchment area, potable water demand, number of residents or users in the building, rainwater demand (as a percentage of potable water demand), and capacity of the upper rainwater tank. Then, Netuno estimates the potential for potable water savings for a range of lower rainwater tank capacities chosen by the user.

Daily rainfall data for Florianópolis were obtained from *Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina* (EPAGRI) for a seven-year time series, i.e., 2000–2006. The catchment surface was taken as the roof area and obtained from Minku (2005), who surveyed 47 office buildings in Florianópolis, including the ten buildings considered in this work. The daily potable water demand per user and the number of users were obtained from Proença (2007). The rainwater demand for toilet flushing was obtained from Proença and Ghisi (2010), who studied the same ten buildings. In all simulations, rainwater losses of 20 % were assumed (Ghisi 2010).

The analysis was performed by considering two rainwater tanks for each building. A lower tank, located at ground level, receives the rainwater from the catchment surface and an upper tank, located on the roof, receives rainwater from the lower tank by a pumping system. The rainwater is taken to the plumbing fixtures (only toilets in this work) by gravity.

To obtain the lower tank capacity, simulations were performed for tank capacities up to 15,000 l at increments of 1,000 l. The ideal lower rainwater tank (the one to be used) was chosen by comparing the potable water savings for each tank capacity, i.e., the ideal tank was the one in which the potential for potable water savings increased 0.5 % or less by increasing the tank capacity in 1,000 l.

As for the upper tank capacity, it was first taken as the daily rainwater demand in the building. Then, such a capacity was decreased (considering figures rounded up to multiple of 500 l). The ideal upper tank capacity was the one in which the potential for potable water savings decreased 0.5 % or less by decreasing the upper tank capacity in 500 l. This procedure was carried out by considering the ideal lower rainwater tank capacity.

The office buildings analysed in this work are not occupied over the weekends, therefore, all simulations took into account that there is water consumption over the weekdays only.

Output data obtained from Netuno and considered in this work were upper and lower tank capacities, and potential for potable water savings for the ten buildings.

3.2 Greywater Reuse

The potential for potable water savings by reusing greywater was estimated considering that greywater from lavatory taps could be reused for toilet flushing. Water end-uses shown in Proença and Ghisi (2010) for the same ten buildings were used. In all ten buildings the greywater demand (toilet flushing) is greater than greywater generation (lavatory taps). Thus, the potable water consumption when there is greywater reuse was estimated by using Eq. 1.

$$C = C_t - C_{taps} \quad (1)$$

where C is the potable water consumption when there is greywater reuse (litres/month); C_t is the total potable water consumption before greywater is introduced (litres/month); C_{taps} is the potable water consumption in lavatory taps, which is recycled as greywater (litres/month).

Therefore, the potential for potable water savings by reusing greywater is the same as the potable water consumption in lavatory taps.

Greywater is to be filtered in gravel filters. Like in the rainwater system, two greywater tanks will be used, i.e., one at ground level and another on the roof. Pumping will be used to take treated greywater from the lower to the upper tank.

3.3 Water-Saving Plumbing Fixtures

To assess the potential for potable water savings by using water-saving plumbing fixtures, the replacement of toilets and taps was analysed. None of the ten buildings currently use water saving fixtures.

3.3.1 Water-Saving Toilets

In this study, bowl-and-tank toilets with tank capacity of 6 l, and dual-flush toilets with tank capacities of 3 and 6 l were considered.

First, the monthly water consumption for any type of toilet flushing was estimated by using Eq. 2.

$$C_{tf} = \sum_{i=1}^n (N \cdot T \cdot V \cdot D)_i \tag{2}$$

where C_{tf} is the estimated monthly water consumption for toilet flushing (litres/month); N is the daily number of times the toilet is flushed (number of times per day); T is the time the toilet is flushed (seconds/use); V is the toilet water flow (l/s); D is the number of working days in a month (days/month); n is the number of users in the building.

In order to ease any discrepancy between the estimated and measured water consumption, the water consumption for toilet flushing was corrected by means of a sensitivity analysis. Therefore, the water consumption estimated by using Eq. 2 was corrected by using Eq. 3.

$$C_{tfc} = C_{tf} \pm D_{tf} \tag{3}$$

where C_{tfc} is the corrected monthly water consumption for toilet flushing (litres/month); C_{tf} is the monthly water consumption for toilet flushing (litres/month); D_{tf} is the difference between estimated and measured monthly water consumption, due to toilet flushing (litres/month).

The water consumption for toilet flushing when using bowl-and-tank toilets with tank capacity of 6 l was estimated by using Eq. 2, but T was taken as 1 s and V , 6 l/s. Such consumption was then corrected by using Eq. 4.

$$C_{6Lc} = C_{tfc} - C_{tfc} \cdot \frac{C_{6L}}{C_{tf}} \tag{4}$$

where C_{6Lc} is the corrected monthly water consumption for toilet flushing when using bowl-and-tank toilets with tank capacity of 6 l (litres/month); C_{tfc} is the corrected monthly water consumption for toilet flushing (litres/month); C_{6L} is the monthly water consumption for toilet flushing when using bowl-and-tank toilets with tank capacity of 6 l (litres/month); C_{tf} is the estimated monthly water consumption for toilet flushing (litres/month).

The water consumption for toilet flushing when using dual-flush toilets was estimated by using Eq. 5. Three scenarios were taken into account assuming that (a) 90 % of flushes take 3 l and 10 % take 6 l; (b) 70 % of flushes take 3 l and 30 %, 6 l; and (c) 50 % of flushes take 3 l and 50 %, 6 l.

$$C_{dual} = \alpha_6 \cdot C_{6Lc} + \alpha_3 \cdot \frac{C_{6Lc}}{2} \tag{5}$$

where C_{dual} is the monthly water consumption for toilet flushing when using dual-flush toilets (litres/month); C_{6Lc} is the corrected monthly water consumption for toilet flushing when using bowl-and-tank toilets with tank capacity of 6 l (litres/month); α_6 is the percentage of flushes with 6 l (%/100); α_3 is the percentage of flushes with 3 l (%/100).

3.3.2 Water-Saving Taps

According to ANA et al. (2005), the use of water-saving taps compared to conventional taps can reduce water consumption by about 40 %. Such figure was used in this work and therefore the water consumption for taps was estimated by using Eq. 6.

$$C_{TE} = 0.6 \times C_{TC} \quad (6)$$

where C_{TE} is the water consumption due to water-saving taps (%); C_{TC} is the water consumption due to conventional taps (%).

3.4 Combining Alternatives

Three scenarios were considered as shown below. The potential for potable water savings were estimated as explained above in Sections 3.1–3.3.

3.4.1 Dual-Flush Toilets and Water-Saving Taps

The maximum potential for potable water savings by using water-saving plumbing fixtures was assessed by combining taps and dual-flush toilets. For toilets, only the best scenario was considered, i.e., 90 % of flushes taking 3 l and 10 %, 6 l.

3.4.2 Rainwater and Greywater

In the scenario combining rainwater and greywater, rainwater was used to supplement greywater. Therefore, rainwater demand was estimated by using Eq. 7.

$$D_f = D_o - O_{reuse} \quad (7)$$

where D_f is the non-potable water demand due to be supplied by rainwater (%); D_o is the water demand for toilet flushing (%); O_{reuse} is the greywater from taps (%).

The potential for potable water savings due to rainwater usage was then estimated by using Netuno.

3.4.3 Rainwater, Greywater and Water-Saving Plumbing Fixtures

In order to assess the combination of all alternatives together, the following order was considered: (a) First, taps and toilets are used as shown in Section 3.4.1. (b) Then, greywater from taps is used for toilet flushing. (c) Finally, in case there is not enough greywater for toilet flushing, rainwater is used.

3.5 Embodied Energy

In order to assess the environmental impact of using rainwater, reusing greywater and installing water-saving taps and dual-flush toilets, an analysis of the embodied energy of components and systems was performed.

The assessment was performed by taking embodied energy indices (in MJ/kg) and weight (in kg) for materials and components used in Brazil, shown in Tavares (2006). The weight for water tanks and pumps were obtained from manufacturers such as Acqualife (2008) and Schneider (2008), respectively. Rainwater and greywater systems were sized considering components such as pipes, tanks, pumps, concrete bricks, gravel and plumbing fixtures.

In order to compare the alternatives, an indicator relating potable water savings (m^3/month) and embodied energy (GJ) was estimated for the four main alternatives. The greater this indicator, the more efficient the alternative as there will be greater potable water savings per GJ of embodied energy.

3.5.1 Embodied Energy in the Rainwater System

For the rainwater system, embodied energy was estimated for the following components:

- Upper and lower rainwater tanks made of reinforced glass fibre;
- Water pipes made of PVC;
- Two pumps to move rainwater from the lower to the upper tank (one pump is spare according to Brazilian standards).

3.5.2 Embodied Energy in the Greywater System

For the greywater system, embodied energy was estimated for the following components:

- Upper and lower greywater tanks made of reinforced glass fibre;
- Sewage pipes made of PVC;
- Water pipes made of PVC;
- Concrete bricks, used to make a filter for greywater treatment;
- Two pumps to move greywater from the lower to the upper tank (one is spare).

3.5.3 Embodied Energy in the Plumbing Fixtures

For the scenario considering dual-flush toilets and water-saving taps, it was assumed that all toilets and taps would be replaced in each building. Thus, the embodied energy for this alternative corresponds to the embodied energy in all toilets and taps.

3.5.4 Sizing the Components of the Systems

The sizing of the water system was performed according to the Brazilian standard NBR 5626 (ABNT 1998). The length of water and sewage pipes was estimated by using the dimensions of the floor plan, the location of bathrooms and the height of the building. A 10 % increment was taken in order to ease any under-sizing, as valves and pipe connections were not considered.

The rainwater tank capacities were estimated by using Netuno, as explained in Section 3.1.

The greywater treatment system was chosen according to recommendations of the Brazilian standard NBR 13969 (ABNT 1997), which suggests a filter with sand or gravel.

As for the greywater tanks, upper and lower tanks with the same capacity were chosen. The total capacity equals the daily greywater generation.

Table 1 Water end-uses in the ten office buildings

Building	Monthly water consumption									
	Taps		Toilets		Cleaning		Others		Total	
	(m ³)	(%)	(m ³)	(%)	(m ³)	(%)	(m ³)	(%)	(m ³)	(%)
Aliança	23.0	8.4	148.0	54.0	7.0	2.6	96.0	35.0	274.0	100.0
Ewaldo Moritz	8.9	6.8	110.2	84.6	2.1	1.6	9.2	7.0	130.3	100.0
Granemann	29.3	27.3	69.4	64.6	2.3	2.1	6.5	6.0	107.5	100.0
Ilha de Santorini	23.9	14.5	130.4	79.1	2.5	1.5	8.0	4.9	164.8	100.0
Ilha dos Ventos	7.4	13.4	44.7	81.0	1.2	2.1	1.9	3.5	55.1	100.0
Manhattan	22.1	19.4	81.2	71.5	4.8	4.3	5.4	4.8	113.6	100.0
Olmiro Faraco	24.5	17.0	113.2	78.5	2.6	1.8	3.7	2.6	144.1	100.0
Pedro Xavier	62.4	23.8	143.4	54.8	7.1	2.7	48.9	18.7	261.9	100.0
Trajanus	56.6	38.4	82.1	55.8	1.8	1.2	6.7	4.5	147.1	100.0
Via Venneto	12.4	14.4	44.6	52.0	3.3	3.9	25.5	29.7	85.7	100.0

4 Results

4.1 Water End-Uses and Demand

Data regarding water end-uses are summarized in Table 1. It can be observed that toilet flushing represents more than half of the water consumption in the buildings studied, varying between 52.0 and 84.6 %. Roof area, total water demand, number of occupants and non-potable water demand for each building are presented in Table 2. All buildings are supplied with potable water; so, the total water demand is the same as the potable water demand prior to any interventions.

Total water demand varies greatly amongst the ten buildings, ranging from 34.9 to 101.6 l per capita/day. This is due mostly to the diversity of commercial activities developed in each building and by their floating population. In order to estimate the non-potable water demand, it was considered that water consumed for toilet flushing could be replaced by non-potable water.

Table 2 Roof area, total water demand, number of users and non-potable water demand for the ten buildings

Building	Roof area (m ²)	Total water demand (litres per user/day)	Number of users	Non-potable water demand (%)
Aliança	233.6	84.1	157	54.0
Ewaldo Moritz	158.6	65.4	96	84.6
Granemann	145.6	101.6	51	64.6
Ilha de Santorini	150.5	53.7	148	79.1
Ilha dos Ventos	133.6	34.9	76	81.0
Manhattan	220.7	39.7	138	71.5
Olmiro Faraco	312.4	48.6	143	78.5
Pedro Xavier	288.2	51.9	243	54.8
Trajanus	299.3	55.4	128	55.8
Via Venneto	154.6	53.6	100	52.0

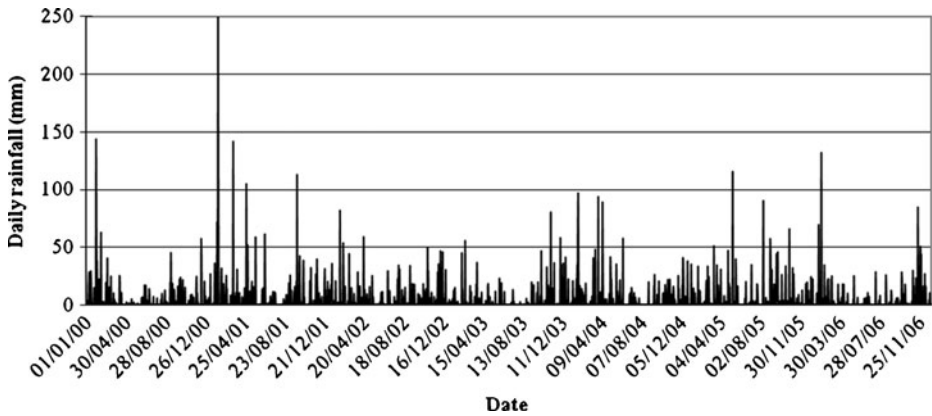


Fig. 1 Daily rainfall for Florianópolis over 2000–2006

4.2 Rainwater Harvesting

The first option considered to reduce potable water consumption was rainwater harvesting. By using the Netuno computer programme, the operation of a rainwater harvesting system with two rainwater tanks (upper and lower tanks) was simulated. Simulations were performed using daily rainfall for the city of Florianópolis over the period January 2000 to December 2006 (Fig. 1). Average annual rainfall is 1595 mm.

From the computer simulations, the potential for potable water savings considering lower rainwater tanks with different capacities was obtained. Figure 2 shows the potential for potable water savings that could be achieved for the ten buildings. To obtain such results, the capacity of the upper tank for each building was previously calculated. The greatest potential for potable water savings were obtained for the Ilha dos Ventos building; the adoption of a lower tank with a capacity of 6,000 l would allow for 21.2 % of potable water savings. Variations in the potential for potable water savings amongst the ten buildings are mainly due to the relation between roof area and rainwater demand.

Ideal upper and lower tank capacities are presented in Table 3. As an attempt to reduce the upper tank capacity, after choosing the ideal capacity of the lower tank, the

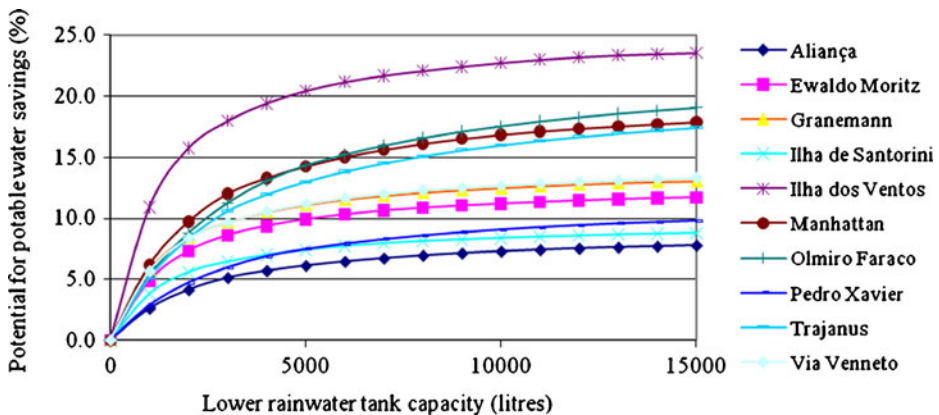


Fig. 2 Potential for potable water savings as a function of rainwater tank capacity for the ten buildings

Table 3 Potential for potable water savings by using rainwater and ideal tank capacities

Building	Daily water consumption (m ³)	Rainwater demand		Potential for potable water savings		Lower tank capacity (litres)	Upper tank capacity (litres)
		(m ³ /day)	(%)	(m ³ /day)	(%)		
Aliança	13.2	7.1	54.0	0.81	6.1	5000	3000
Ewaldo Moritz	6.3	5.3	84.6	0.62	9.9	5000	2500
Granemann	5.2	3.3	64.6	0.58	11.1	5000	2000
Ilha de Santorini	7.9	6.3	79.1	0.56	7.0	4000	2000
Ilha dos Ventos	2.7	2.2	81.0	0.56	21.2	6000	2000
Manhattan	5.5	3.9	71.5	0.85	15.6	7000	3000
Olmiro Faraco	6.9	5.5	78.5	1.19	17.1	9000	4500
Pedro Xavier	12.6	6.9	54.8	1.00	7.9	6000	4000
Trajanus	7.1	4.0	55.8	1.07	15.1	8000	3000
Via Venneto	5.4	2.8	52.0	0.60	11.2	5000	2000

upper tank capacity was gradually reduced (in 500 l intervals). It was considered that the capacity could be reduced to a maximum of 0.5 % difference to the potable water savings estimated for the initial capacities. Thus, as an example, in Pedro Xavier building the adoption of an upper tank of 4,000 l would allow for 7.9 % potable water savings. In case the capacity of the upper tank were taken to be the same as the daily rainwater demand, i.e., 7,000 l, the increase in potable water savings would be less than 0.5 %.

Daily water consumption and rainwater demand were calculated based on the water consumption and number of occupants of each building. Potential for potable water savings varied between 6.1 and 21.2 %. For instance, in the Aliança building the ideal capacities for the lower and upper tanks are 5,000 and 3,000 l, respectively. Potable water savings corresponded to 6.1 % only (equivalent to 0.81 m³/day). The low potentials for potable water savings observed are mainly due to high rainwater demands combined with small roof areas.

Table 4 Potential for potable water savings by reusing greywater

Building	Greywater demand (m ³ /month)	Greywater generation (m ³ /month)	Savings by reusing greywater (m ³ /month)
Aliança	148.0	23.0	23.0
Ewaldo Moritz	110.2	8.9	8.9
Granemann	69.4	29.3	29.3
Ilha de Santorini	130.4	23.9	23.9
Ilha dos Ventos	44.7	7.4	7.4
Manhattan	81.2	22.1	22.1
Olmiro Faraco	113.2	24.5	24.5
Pedro Xavier	143.4	62.4	62.4
Trajanus	82.1	56.6	56.6
Via Venneto	44.6	12.4	12.4

Table 5 Potable water savings by using bowl-and-tank toilets and dual-flush toilets

Building	Parameter	Conventional toilet	Bowl-and-tank toilet (6 litres)	Dual-flush toilet	
				(90 % of flushes with 3 litres)	(50 % of flushes with 3 litres)
Aliança	Water consumption (m ³ /month)	148.0	153.8	84.6	100.0
	Savings (%)	–	–2.1	23.1	17.5
Ewaldo Moritz	Water consumption (m ³ /month)	110.2	64.3	35.4	41.8
	Savings (%)	–	35.2	57.4	52.5
Granemann	Water consumption (m ³ /month)	69.4	52.1	28.7	33.9
	Savings (%)	–	16.1	37.9	33.1
Ilha de Santorini	Water consumption (m ³ /month)	130.4	66.1	36.4	43.0
	Savings (%)	–	39.0	57.0	53.0
Ilha dos Ventos	Water consumption (m ³ /month)	44.7	35.9	19.7	23.3
	Savings (%)	–	15.9	45.2	38.7
Manhattan	Water consumption (m ³ /month)	81.2	79.1	43.5	51.4
	Savings (%)	–	1.9	33.2	26.3
Olimiro Faraco	Water consumption (m ³ /month)	113.2	69.7	38.3	45.3
	Savings (%)	–	30.2	52.0	47.1
Pedro Xavier	Water consumption (m ³ /month)	154.2	158.0	86.9	102.7
	Savings (%)	–	–1.4	25.7	19.7
Trajanus	Water consumption (m ³ /month)	82.1	91.3	50.2	59.4
	Savings (%)	–	–6.3	21.6	15.4
ViaVenneto	Water consumption (m ³ /month)	44.6	32.3	17.8	21.0
	Savings (%)	–	14.3	31.2	27.5

4.3 Reuse of Greywater

The potential for potable water savings by reusing greywater was estimated considering that water from taps could be reused for toilet flushing. Such savings are presented in Table 4. It can be observed that potable water savings vary from 7.4 to 62.4 m³/month, corresponding to 6.8–38.4 % of the monthly water consumption in these buildings.

For instance, in the Aliança building, the consumption of potable water to flush toilets (which represents the greywater demand) amounts to 148.0 m³/month. In the same building, water used in taps amounts to 23.0 m³/month, which represents the volume of greywater available to be used for toilet flushing. Thus, the potable water savings in this building equals to 23.0m³month (equivalent to 8.4 % of the total water consumption). The greywater demand (toilet flushing) is greater than the greywater generation (effluent from taps) in all ten buildings considered in this study. The reuse of greywater presented a greater potential for potable water savings than rainwater harvesting in eight out of the ten buildings. Only in Ewaldo Moritz and Ilha dos Ventos buildings rainwater harvesting presented a greater potential for potable water savings than greywater reuse, due mostly to low water consumption from taps in these buildings.

4.4 Adoption of Dual-Flush Toilets

Table 5 presents the water consumption due to conventional, bowl-and-tank, and dual-flush toilets. The adoption of bowl-and-tank toilets increased the consumption of water in three buildings (Aliança, Pedro Xavier and Trajanus) since the average water consumption for toilet flushing was lower than 6 l per flush in these buildings.

In the Aliança building, for example, toilet flushing is responsible for the consumption of 148.0 m³/month of potable water. If bowl-and-tank toilets with tanks of 6 l were adopted, water consumption would increase to 153.8 m³/month (a 2.1 % increase in the water consumption of this building). On the other hand, the adoption of dual-flush toilets would reduce the water consumption between 11.9 and 23.1 %, depending on the dual-flush scenario.

The adoption of dual-flush toilets reduced considerably the water consumption in the three scenarios analysed. The less efficient scenario (use of 3 l per flush in 50 % of the times) presented reductions on the total water consumption between 9.2 and 49.0 %. Intermediate scenario (use of 3 l per flush in 70 % of the times) presented reductions between 15.4 and 53.0 %. The more efficient scenario (use of 3 l per flush in 90 % of the times) presented reductions between 21.6 and 57.4 %.

Table 6 Potable water savings by replacing conventional taps with water-saving taps

Building	Potential for potable water savings	
	(m ³ /month)	(%)
Aliança	9.2	3.4
Ewaldo Moritz	3.6	2.7
Granemann	11.7	10.9
Ilha de Santorini	9.5	5.8
Ilha dos Ventos	3.0	5.4
Manhattan	8.9	7.8
Olmiro Faraco	9.8	6.8
Pedro Xavier	24.9	9.5
Trajanus	22.7	15.4
Via Venneto	5.0	5.8

Table 7 Potable water savings by combining the use of dual-flush toilets and water-saving taps

Building	Potential for potable water savings	
	(m ³ /month)	(%)
Aliança	72.6	26.5
Ewaldo Moritz	78.4	60.1
Granemann	52.5	48.8
Ilha de Santorini	103.6	62.9
Ilha dos Ventos	27.9	50.6
Manhattan	46.6	41.0
Olmiro Faraco	84.7	58.8
Pedro Xavier	92.3	35.3
Trajanus	54.4	37.0
Via Venneto	31.7	37.0

4.5 Adoption of Water-Saving Taps

To evaluate the impact of using water-saving taps, a 40 % reduction on water consumption (compared to conventional taps) was considered, in agreement with data presented in ANA et al. (2005). Results are presented in Table 6. It can be observed that this measure could reduce the total water consumption in the buildings between 2.7 and 15.4 %. Thus, the use of water-saving taps is a measure not as efficient as the adoption of dual-flush toilets.

4.6 Combined Alternatives for Efficient use of Water

4.6.1 Combining Dual-Flush Toilets and Water-Saving Taps

This alternative corresponds to the maximum potential for water savings by using water-saving plumbing fixtures. The most efficient scenario of dual-flush toilets (use of 3 l per flush in 90 % of the times) was considered together with the adoption of water-saving taps.

Table 8 Potential for potable water savings by using rainwater when there is greywater reuse to supply the non-potable water demand

Building	Non-potable water demand (%)	Greywater generation (%)	Rainwater demand (%)	Potable water savings by using rainwater (%)	Ideal lower tank capacity (litres)	Ideal upper tank capacity (litres)
Aliança	54.0	8.4	45.6	6.1	5000	3000
Ewaldo Moritz	84.6	6.8	77.7	9.9	5000	2500
Granemann	64.6	27.3	37.3	10.8	5000	1500
Ilha de Santorini	79.1	14.5	64.6	7.0	4000	2000
Ilha dos Ventos	81.0	13.4	67.6	21.2	7000	1500
Manhattan	71.5	19.4	52.1	15.8	8000	2500
Olmiro Faraco	78.5	17.0	61.5	16.6	9000	3500
Pedro Xavier	54.8	23.8	30.9	7.0	5000	2500
Trajanus	55.8	38.4	17.3	11.8	7000	1500
Via Venneto	52.0	14.4	37.6	10.8	5000	1500

Table 9 Potential for potable water savings by combining rainwater and greywater

Building	Non-potable water demand for toilet flushing (m ³ /month)	Non-potable water generation (m ³ /month)		Potential for potable water savings	
		Taps	Rainwater	(m ³ /month)	(%)
Aliança	148.0	23.0	16.7	39.7	14.5
Ewaldo Moritz	110.2	8.9	12.9	21.8	16.8
Granemann	69.4	29.3	11.6	40.9	38.1
Ilha de Santorini	130.4	23.9	11.5	35.5	21.5
Ilha dos Ventos	44.6	7.4	11.7	19.1	34.6
Manhattan	81.3	22.1	17.9	40.0	35.2
Olmiro Faraco	113.2	24.5	23.9	48.5	33.6
Pedro Xavier	143.4	62.4	18.3	80.7	30.8
Trajanus	82.1	56.6	17.4	73.9	50.2
Via Venneto	44.6	12.4	9.3	21.6	25.2

Results are presented in Table 7. The potential for potable water savings ranged from 26.5 to 62.9 % (corresponding to potable water savings of 27.9–103.9 m³/month).

4.6.2 Combining Rainwater Harvesting and Greywater Reuse

To evaluate the potential for potable water savings by combining rainwater and greywater reuse, reuse was considered first since greywater is generated in the building and its availability does not depend on climatic conditions. The remaining demand was used as input data to run the simulations to estimate the potential for potable water savings by using rainwater. Results are shown in Table 8.

The potential for potable water savings by combining both alternatives are presented in Table 9. The potential for potable water savings due to rainwater harvesting

Table 10 Potential for rainwater usage when there are water-saving plumbing fixtures and greywater reuse to supply the non-potable water demand

Building	Non-potable water demand (%)	Greywater generation (%)	Rainwater demand (%)	Potable water savings by using rainwater (%)	Ideal lower tank capacity (litres)	Ideal upper tank capacity (litres)
Aliança	30.9	5.0	25.9	5.4	4000	2000
Ewaldo Moritz	27.2	4.1	23.1	9.3	5000	1500
Granemann	26.7	16.4	10.3	7.5	4000	500
Ilha de Santorini	22.1	8.7	13.4	6.3	4000	1000
Ilha dos Ventos	35.8	8.0	27.7	19.1	7000	1000
Manhattan	38.3	11.6	26.6	14.7	8000	1500
Olmiro Faraco	22.6	14.2	8.5	5.9	3000	500
Pedro Xavier	29.1	14.3	14.8	6.3	5000	1500
Trajanus	34.2	23.0	11.1	8.7	5000	1000
Via Venneto	20.8	8.6	12.1	8.5	4000	1000

Table 11 Potential for potable water savings by combining rainwater, greywater and water-saving plumbing fixtures

Building	Savings due to plumbing fixtures replacement (%)	Savings due to non-potable water generation (%)		Potential for potable water savings (%)
		Taps	Rainwater	
Aliança	26.5	5.0	5.4	36.9
Ewaldo Moritz	60.1	4.1	9.3	73.5
Granemann	48.8	16.4	7.5	72.8
Ilha de Santorini	62.9	8.7	6.3	77.9
Ilha dos Ventos	50.6	8.0	19.1	77.7
Manhattan	41.0	11.6	14.7	67.3
Olmiro Faraco	58.8	14.2	5.9	78.9
Pedro Xavier	35.3	14.3	6.3	55.8
Trajanus	34.2	23.0	8.7	68.7
Via Venneto	37.0	8.6	8.5	54.1

are slightly lower when this alternative is combined with greywater reuse (Table 8), compared to rainwater harvesting only (Table 3). This fact is a result of the methodology adopted for the calculation of the rainwater tank capacities. As the rainwater demand is lower when there is the combination of alternatives, the tank capacities required were up to 1.5 m³ smaller.

The potential for potable water savings considering both alternatives varied between 14.5 and 50.2 % (Table 9). For instance, the Aliança building had a non-potable water demand (toilet flushing) of 148.0 m³/month and an availability of greywater (effluent from taps) of 23.0 m³/month. The difference between non-potable water demand and greywater availability represents the rainwater demand (input data for Netuno, as shown in Table 8). Thus, non-potable water availability corresponds to the sum of greywater and rainwater availability. For the Aliança building, potable water savings correspond to 39.7 m³/month, or 14.5 % of the total potable water consumption.

Table 12 Embodied energy in the rainwater system of Aliança Building

Materials and components	Quantity	Unit	Weight (kg/unit)	Embodied energy (MJ/kg)	Total embodied energy (MJ)	Total embodied energy (%)
5000-litre glass fibre tank	1	tank	76.1	24	1825	7
3000-litre glass fibre tank	1	tank	47.3	24	1136	4
PVC water pipes (25 mm)	33	m	0.7	80	1696	6
PVC water pipes (50 mm)	137	m	1.1	80	12,286	44
PVC water pipes (65 mm)	74	m	1.7	80	10,110	37
Pumps (1 hp)	2	pump	10.4	31	645	2
Total	–	–	–	–	27,698	100

Table 13 Embodied energy in the greywater system of Aliança Building

Materials and components	Quantity	Unit	Weight (kg/unit)	Embodied energy (MJ/kg)	Total embodied energy (MJ)	Total embodied energy (%)
1000-litre glass fibre tank	2	tank	20.0	24	960	3
PVC water pipes (25 mm)	33	m	0.7	80	1696	4
PVC water pipes (50 mm)	137	m	1.1	80	12,286	32
PVC water pipes (65 mm)	74	m	1.7	80	10,110	27
PVC sewage pipes (40 mm)	137	m	0.4	80	3839	10
PVC sewage pipes (50 mm)	65	m	0.4	80	2087	5
PVC sewage pipes (75 mm)	15	m	0.5	80	601	2
Pumps (1 hp)	2	pump	7.0	31	434	1
Concrete bricks	437	brick	12.2	1	5307	14
Gravel	3	m ³	1650.0	0.15	792	2
Total	–	–	–	–	38,113	100

4.6.3 Combining Rainwater, Greywater and Water-Saving Plumbing Fixtures

When combining the three alternatives, water-saving plumbing fixtures were taken as the first option and greywater as the second option considered. Table 10 presents the potential for potable water savings by using rainwater, taking into account the adoption of water-saving plumbing fixtures and greywater reuse. For instance, the adoption of dual-flush toilets in the Aliança building reduced the non-potable water demand from 54.0 to 30.9 % of the total water consumption. The adoption of water-saving taps reduced the availability of greywater from 8.4 to 5.0 %. Thus, the rainwater demand corresponds to the difference between toilet flushing demand (30.9 %) and availability of greywater (5.0 %).

The potential for potable water savings considering the three alternatives combined ranged between 36.9 and 78.9 % (Table 11). Olmiro Faraco building presented the greatest potential for potable water savings. In this building, the adoption of water-saving plumbing fixtures would reduce potable water consumption by 58.8 %; and by combining the three alternatives, potable water consumption would be reduced by 78.9 %.

4.7 Embodied Energy

In order to compare the environmental impact of different alternatives to reduce potable water consumption, embodied energy in the main components of each of the four main

Table 14 Embodied energy for the water-saving plumbing fixtures of Aliança Building

Materials and components	Quantity	Unit	Weight (kg/unit)	Embodied energy (MJ/kg)	Total embodied energy (MJ)	Total embodied energy (%)
Toilet with accessories	42	toilet	15.0	25	15,750	60
Sink with water-saving tap and accessories	42	sink	10.0	25	10,500	40
Total	–	–	–	–	26,250	100

Table 15 Embodied energy and potable water savings for the four main alternatives analysed

Building	Alternative	Embodied energy (MJ)	Potable water savings		Indicator of potable water savings per embodied energy (m ³ /month.GJ)
			(m ³ /month)	(%)	
Aliança	Rainwater usage	27,691	16.7	6.1	0.60
	Greywater reuse	38,113	23.0	8.4	0.60
	Dual-flush toilets	15,750	63.4	23.1	4.03
	Water-saving taps	10,500	9.2	3.4	0.87
Ewaldo Moritz	Rainwater usage	9,834	12.9	9.9	1.31
	Greywater reuse	13,196	8.9	6.8	0.67
	Dual-flush toilets	6,750	74.8	57.4	11.08
	Water-saving taps	4,500	3.6	2.7	0.79
Granemann	Rainwater usage	12,834	11.9	11.1	0.93
	Greywater reuse	22,476	29.3	27.3	1.31
	Dual-flush toilets	4,875	40.8	37.9	8.36
	Water-saving taps	3,250	11.7	10.9	3.61
Ilha de Santorini	Rainwater usage	11,212	11.5	7.0	1.03
	Greywater reuse	20,311	23.9	14.5	1.18
	Dual-flush toilets	6,750	94.0	57.0	13.93
	Water-saving taps	4,500	9.6	5.8	2.13
Ilha dos Ventos	Rainwater usage	15,097	11.7	21.2	0.77
	Greywater reuse	20,163	7.4	13.4	0.37
	Dual-flush toilets	12,000	24.9	45.2	2.08
	Water-saving taps	8,000	3.0	5.4	0.37
Manhattan	Rainwater usage	25,423	17.7	15.6	0.70
	Greywater reuse	42,391	22.0	19.4	0.52
	Dual-flush toilets	21,375	37.7	33.2	1.77
	Water-saving taps	14,250	8.8	7.8	0.62
Olmiro Faraco	Rainwater usage	19,262	24.6	17.1	1.28
	Greywater reuse	27,440	30.3	21.0	1.10
	Dual-flush toilets	12,000	74.9	52.0	6.24
	Water-saving taps	8,000	9.8	6.8	1.23
Pedro Xavier	Rainwater usage	24,776	20.7	7.9	0.84
	Greywater reuse	42,042	62.3	23.8	1.48
	Dual-flush toilets	28,125	67.3	25.7	2.39
	Water-saving taps	18,750	25.0	9.5	1.33
Trajanus	Rainwater usage	18,774	22.2	15.1	1.18
	Greywater reuse	32,834	56.5	38.4	1.72
	Dual-flush toilets	13,500	31.8	21.6	2.36
	Water-saving taps	9,000	22.6	15.4	2.51
ViaVenneto	Rainwater usage	17,542	9.6	11.2	0.55
	Greywater reuse	25,701	12.3	14.4	0.48
	Dual-flush toilets	9,750	26.8	31.2	2.75
	Water-saving taps	6,500	4.9	5.8	0.76

alternatives was estimated. Rainwater harvesting and greywater reuse systems were dimensioned, considering only their key components (pipes, tanks, pumps, concrete bricks and plumbing fixtures). As an example, results for the Aliança building are presented in Tables 12, 13 and 14. Reuse of greywater was the alternative with the highest embodied energy (38 GJ), followed by rainwater harvesting (28 GJ) and water-saving plumbing fixtures (26 GJ). It can be observed that pipes correspond to 87 % of the embodied energy in the rainwater system and 80 % in the greywater system. Thus, more detailed dimensioning of pipes is advised for future works, in order to get more precise results. Table 15 summarises the results for the ten buildings.

In Table 15, it can be observed that greywater reuse presents the highest embodied energy among the alternatives in all buildings, followed by rainwater harvesting in nine out of ten buildings. Only one building presented the adoption of dual-flush toilets as the second alternative with the highest embodied energy, due to the great number of toilets in the building. To ease comparisons, monthly water savings (m^3/month) were divided by the embodied energy (GJ) of each alternative, thus creating an indicator of potable water savings per unit of embodied energy. Such an indicator shows that dual-flush toilets are the most efficient alternative regarding the use of water and embodied energy in all buildings, presenting the highest potable water savings per GJ of embodied energy. On average, the potable water savings per embodied energy for dual-flush toilets were $5.50 \text{ m}^3/\text{month}$ per GJ, followed, respectively, by water-saving taps ($1.42 \text{ m}^3/\text{month.GJ}$), greywater reuse ($0.94 \text{ m}^3/\text{month.GJ}$), and rainwater usage ($0.92 \text{ m}^3/\text{month.GJ}$).

5 Conclusions

The main objective of this study was to evaluate the potential for potable water savings in ten office buildings located in the city of Florianópolis (Brazil) and assess the environmental impact by estimating the embodied energy for some of the alternatives considered. Analyses were based on water end-uses for the ten buildings. The alternatives for potable water savings considered were greywater reuse, rainwater harvesting, dual-flush toilets and water-saving taps.

The assessment of potable water savings showed that dual-flush toilets provided the greatest savings, which ranged from 9.2 to 57.4 % amongst the ten buildings; and were followed, respectively, by greywater reuse (6.8–38.4 % savings), rainwater usage (6.1–21.2 % savings), and water-saving taps (2.7–15.4 % savings). By combining these alternatives, the greatest savings were obtained, respectively, by the four alternatives together (36.9–78.9 % savings), by dual-flush toilets and water-saving taps (26.5–62.9 % savings), and by rainwater and greywater (14.5–50.2 % savings).

Evaluation of the embodied energy in the main components of the four main alternatives was performed based on embodied energy indices for materials used in Brazil. It was verified that greywater reuse is the alternative with the highest embodied energy (13–42 GJ), followed by rainwater harvesting (10–28 GJ), dual-flush toilets (5–28 GJ) and water-saving taps (3–19 GJ), indicating that water-saving taps could possibly be the most suitable alternative. However, despite the fact that water-saving taps have a lower embodied energy, the potential for potable water savings is the lowest between the alternatives considered.

Therefore, by combining both analyses, it was observed that the adoption of dual-flush toilets can be considered the most efficient and environmentally friendly alternative, once it allows for the greatest potable water savings per GJ of embodied energy. It is also important

to notice that this alternative does not demand electricity for operation, while greywater and rainwater systems do (electricity demand for pumps). On average, dual-flush toilets provided water savings of 5.50 m³/month per GJ of embodied energy; and water-saving taps were the second best alternative (1.42 m³/month.GJ), followed by greywater reuse (0.94 m³/month.GJ) and rainwater usage (0.92 m³/month.GJ).

This study showed that there is a great potential for potable water savings in office buildings in Florianópolis, and also that embodied energy should be taken into account in order to select the alternatives that will provide for not only low potable water consumption but also low environmental impact.

Although some alternatives considered in this study may not be feasible for actual buildings as they imply several changes in the buildings, the results shown herein indicate that such alternatives should be used as benchmarking for design of new office buildings. This would allow for lower water consumption during the life span of buildings, lower operational costs and lower environmental impact.

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