Water–energy nexus in houses in Brazil: comparing rainwater and gray water use with a centralized system
A. S. Vieira and E. Ghisi

ABSTRACT

The objective of this paper is to assess the potential for energy savings in water and sewerage services by means of on-site integrated water and sewage management strategies in low-income households in Florianópolis, Brazil. The on-site water efficiency measures include reclamation of gray water and rainwater use. The water and energy saving potential of both strategies were studied, and their energy intensities were compared to centralized water and sewerage services. Furthermore, the water consumption pattern for 10 low-income households was empirically determined using smart meters; the rainwater supply was estimated by using the computer program Netuno 4.0; and the water supply and sewage reduction potential of gray water systems were determined using a theoretical method. On average, the gray water and rainwater supply capacities were equivalent to 24% and 43% of the total water consumption of households, respectively. In regard to energy savings, rainwater harvesting was the most energy intensive strategy (0.86 kWh/m³), followed by centralized systems (0.84 kWh/m³); whereas, gray water was the most energy efficient strategy (0.54 kWh/m³). The findings suggest that alternative water and sewerage services may promote energy savings in comparison with centralized ones only when a concomitant reduction in sewage production is achieved.

Key words | gray water reclamation, low-income households, rainwater harvesting, water–energy nexus

INTRODUCTION

The water–energy nexus has been recognised as an overarching concept to improve management practices in the water and energy sectors alike (Gleick 1994; Lofman et al. 2002; Malik 2002; Retamal et al. 2009; Proença et al. 2011; Scott et al. 2011; Ackerman & Fisher 2013). The energy sector depends on water availability for power generation (Glassman et al. 2011), and the water sector demands energy for water pumping and treatment (Lee & Tansel 2012).

In Brazil, the lack of adequate sanitation and housing facilities is common in low-income areas. From 2010 to 2014, the Brazilian government invested approximately R$71.7 billion (US$42.9 billion in December 2010) to address the deficit of low-income housing. In this context, there are opportunities to build low-income houses in which sustainable initiatives are taken into account from a water–energy nexus perspective in order to enhance water and energy services on an urban scale.

The objective of this study is to evaluate the potential for energy savings in water and sewerage services by means of gray water reclamation and rainwater harvesting in low-income households in Florianópolis, southern Brazil.

METHOD

Overview

The study considered a period of 20 years, from 2010 to 2030. The base year (2010) corresponds to the most recent information provided by the National Sanitation
Information System (SNIS) from Brazil SNIS (2012). The scope of the study encompasses the analysis of the most energy intensive phase of the urban water life-cycle, i.e. the operational phase.

**Study period**

The studied period encompassed the same planning horizons as the one adopted by the local government. Therefore, projections for population growth and associated sanitation service augmentations were obtained from government databases from the Community Housing Plan of Florianópolis (PMF 2012) and the Integrated Sanitation Plan of Florianópolis (PMF 2010), respectively.

In the Community Housing Plan of Florianópolis, increases in population densities are estimated of 12.2% between 2010 and 2015, 10.2% between 2015 and 2020, 8.5% between 2020 and 2025, and 7.2% between 2025 and 2030 for Florianópolis city. In order to overcome the lack of centralized sewerage services, the Integrated Sanitation Plan of Florianópolis (PMF 2010) established goals for sewerage augmentations to serve 65%, 77%, 88% and 100% of the population in 2015, 2020, 2025, and 2030, respectively. This sewerage service augmentation goals were incorporated into the assumptions of this study. For water services, the entire population was assumed to be serviced at all times.

**On-site alternative water supply concept**

On-site alternative water supply sources were considered for indoor non-potable water use only. The quality of both rainwater and treated gray water was assumed to be adequate for toilet flushing; whereas, only rainwater was considered as an alternative water supply source for clothes washing. Alternative water supply systems were assumed to be composed of: (i) a water source collection system; (ii) a ground or underground level storage tank; (iii) a distribution header tank; (iv) a pumping system between the storage tank and the header tank; and (v) an ultraviolet disinfection system at the header tank.

**Energy intensity evaluation**

Empirical data related to the energy intensity of water and sewerage services were obtained from the National Sanitation Information System (SNIS) for the period between 2004 and 2010 in Florianópolis (Figure 1). Projections of the energy intensity of water supply services for years within the planning horizon were estimated using the power function derived from the empirical data (i.e. \( y = 0.55x^{-0.352} \)) with a coefficient of determination \((R^2)\) equal to 0.60.

The variation of the energy intensity of sewerage services from 2004 to 2010 had an undetermined trend (Figure 1). This lack of correlation may be attributed to the influence of parameters which vary randomly over time. For instance, the coefficient of determination of a linear function between annual rainfall and energy intensity of sewerage services in Florianópolis was equal to 0.99 for the period between 2006 and 2008. Similar results are described in other studies (e.g. Plappally & Lienhard 2012). This strong correlation shows the significant influence of wet weather flows on the energy intensity of sewerage systems in Florianópolis, as well as the unpredictability of future energy intensities for sewerage system operation. Therefore, a steady trend was assumed for the energy intensity of sewerage services equal to 0.57 kWh/m³ throughout the planning horizon.

The selection of technologies used to provide on-site alternative water and sewerage services was based on the most energy efficient processes available on the market. Therefore, the use of electricity was disregarded for on-site gray water and sewage treatment, which were considered to be performed by constructed vertical wetlands and septic tanks operated by gravity, respectively. The theoretical evaluation of the energy intensity of on-site water and
sewerage services was focused on the energy consumption associated with the pumping and disinfection of alternative water supply systems only.

### Energy intensity of pumping systems

For each alternative water supply system, the operation of two pumps was considered, including: (i) a pump to transfer the daily water demand from rainwater or gray water storage tanks into their respective header tanks once per day; and (ii) a pump to recirculate the water in the header tank into the disinfection system. The power of these two pumps was considered to be equal to the power of pumps available on the market with power equivalent to or immediately above the one calculated using Equation (1):

$$P_P = \frac{\rho \times g \times H \times Q}{\eta_M \times \eta_B}$$  \hspace{1cm} (1)

where $P_P$ is the pump input power rating (W); $\rho$ is the liquid density (kg/m³); $g$ is the gravitational acceleration (m/s²); $H$ is the total head (i.e. geometrical height and friction loss height) (m); $Q$ is the flow rate (m³/s); $\eta_M$ is the motor efficiency (dimensionless); and $\eta_B$ is the pump efficiency (dimensionless). Note: 1 joule is equal to 1 W s and 1 kg m²/s².

Three components of the energy intensity of pumps were considered (Equation (2)), including: start-up, active pumping and standby mode. As per Retamal et al. (2009), it was assumed that the standby mode power rating is equivalent to 2 W, and start-up energy consumption to 30 seconds during active pumping.

$$IE_P = \frac{P_P}{Q} + \left[\frac{(C_{su} \times N_{su}) + (P_{sb} \times t_{sb})}{V}\right]$$  \hspace{1cm} (2)

where $IE_P$ is the energy intensity of the pumping system (kWh/m³); $P_P$ is the pump input power (kW); $Q$ is the flow rate (m³/h); $C_{su}$ is the pump start-up energy consumption (kWh/start-up); $N_{su}$ is the number of start-up events (start-up); $P_{sb}$ is the standby power rating (kW); $t_{sb}$ is the daily period in standby mode (hours); and $V$ is the daily water consumption (m³).

In order to estimate the energy intensity of energy efficient pumping systems, a review of pumps available on the market was carried out. The most energy efficient pumps were selected so as to estimate the energy intensity of the studied alternative water supply systems. Future levels of efficiency of pumping systems were estimated by assuming a reduction of the energy requirements for start-up and standby mode of 50% within the planning horizon.

### Energy intensity of ultraviolet disinfection systems

Disinfection requirements were assumed to be performed by ultraviolet radiation with wavelength of 254 nm (UV-C), hereafter denoted as ‘UV’ only. So as to avoid pathogen growth in the rainwater and gray water header tanks, UV disinfection cycles were considered to occur during the daily pumping of alternative water sources from storage tanks to heater tanks, and at 6-hour intervals thereafter to prevent pathogen regrowth (Friedler et al. 2011).

The total power installed in the UV disinfection systems was composed of the UV lamp and the circulation pump power rates. The power rate of the UV lamps was considered to be equal to the lamps available on the market with power equivalent to or immediately above the one calculated using Equation (3). This equation was derived from the equations described by the North American Environmental Protection Agency (US-EPA 2006) to determine the dose and the intensity of radiation in UV disinfection systems with cylindrical reactors with immersed UV lamps.

$$P_{UV} = \frac{2 \times D \times Q \times (r_2 - r_1) \times e^\alpha(r_2 - r_1)}{E \times R \times L \times (r_2^2 - r_1^2)}$$  \hspace{1cm} (3)

where $P_{UV}$ is the power of the UV lamp (W); $D$ is the UV dose at the furthest point from the UV lamp within the UV reactor (mW s/cm²); $Q$ is the flow rate through the UV reactor (L/s); $r_1$ is the outer radius of the UV lamp sleeve (cm); $r_2$ is the inner radius of the UV reactor (cm); $e$ is Euler’s number (2.71828); $\alpha$ is the absorbance coefficient of UV radiation by fluids (cm⁻¹); $E$ is the transformation coefficient of electricity into UV radiation (dimensionless); $R$ is the radiation emission reduction coefficient during the lifespan of the UV lamps (dimensionless); and $L$ is the lamp sleeve transmittance (dimensionless). The UV radiation dose required for disinfection was calculated using...
Equation (4) (Chick 1908). Utilizing a conservative approach, UV doses were limited to 120 mW s/cm², as pathogens can be completely eliminated by UV doses of 69 mW s/cm² (Gilboa & Friedler 2008).

\[ D = \frac{\ln (N_0) - \ln (N_t)}{k} \]  

where \( D \) is the UV dose of radiation at 254 nm at the most distant point from the UV lamp within the UV reactor (mW s/cm²); \( N_0 \) is the concentration of microorganisms before disinfection (MPN/100 mL); \( N_t \) is the concentration of microorganisms after disinfection (MPN/100 mL); and \( k \) is the first-order coefficient of inactivation (cm²/mW s). The first-order coefficient described by Gilboa & Friedler (2008), i.e. 0.0687 cm²/mW s, was adopted into the UV dose calculations.

The energy intensity of UV disinfection systems was calculated using Equation (5):

\[ IE_{UV} = \sum_{i=1}^{n} (P_{UV} \times \frac{1}{Q} + \frac{t_i}{V}) \]  

where \( IE_{UV} \) is the energy intensity of the UV disinfection system (kWh/m³); \( P_{UV} \) is the installed power in the UV disinfection system (lamps and circulation pump) (kW); \( Q \) is the flow rate in the UV disinfection system (m³/h); \( t_i \) is the activation period for the lamps to reach the maximum UV radiance output (hours); \( V \) is the volume of water to be treated in the UV disinfection system during each disinfection cycle – maximum header tank volume (m³); and \( n \) is the number of disinfection cycles for a stored volume of water (dimensionless).

Energy intensity of on-site alternative water services

The energy intensity of alternative water supply systems was determined by summing the energy intensity of their respective pumping systems (\( IE_P \)) and UV disinfection systems (\( IE_{UV} \)).

Energy intensity of integrated water and sewage management strategies

On-site integrated water and sewerage strategies were composed of the combination of on-site systems (i.e. rainwater harvesting and gray water reclamation) with centralized systems (i.e. municipal water supply and sewage collection and treatment). For strategies with two alternative water supply sources for toilet flushing, gray water took precedence over rainwater. Alternative water and sewerage services were supplemented by centralized ones when on-site systems were either under capacity to meet the total demand, or not suitable to serve a specific water end-use or sewage source use. The energy intensity of each strategy was calculated using Equation (6):

\[ IE_s = \sum_{i=1}^{n} [IE_n \times S_n \times (1 \pm V_n) \times (1 \pm L_n)] \]  

where \( IE_s \) is the energy intensity of the strategy to provide water and sewerage services (kWh/m³); \( n \) is the number of systems adopted in the strategy (dimensionless); \( IE_n \) is the energy intensity of a system (kWh/m³); \( S_n \) is the service capacity of a system (dimensionless); \( V_n \) is the demand variation promoted by a system – positive or negative for increasing or decreasing trends, respectively (dimensionless); and \( L_n \) is the coefficient of losses of a system – positive or negative for losses prior or subsequent to energy consumption, respectively (dimensionless).

Water savings and rebounds on the demand side and supply side management strategies were accounted for by using the demand variation parameter in Equation (6). Similarly, losses in water and sewage flows were also considered in Equation (6). Both parameters have a considerable influence on the energy performance of water and sewerage services.

Water consumption pattern and end-use analysis

The water consumption pattern and end uses were empirically determined during a minimum period of 2 weeks in 10 low-income households in Florianópolis. The determined patterns were used to estimate the potential to use on-site alternative water supply and sewage collection and treatment systems. The water consumption pattern and end uses were recorded using Smart Meters (manufactured by Sustentare Soluções Tecnológicas) with a temporal resolution equal to 1 second and a volumetric resolution equal to 0.014 L/pulse. End-use events were automatically disaggregated by using one Smart
Meter sensor for each water end-use point. The volume and duration of consumption events of taps, showers, washing machines, and toilets with cisterns were recorded.

Water end-uses were categorized by considering the minimum water quality required to supply different end-use points, including: (i) potable water supply only to showers and taps; (ii) non-potable rainwater supply to washing machines and toilets; and (iii) non-potable gray water supply to toilets.

**Integrated water and sewage management strategy analysis**

**Gray water reclamation systems**

The potential water supply and sewage reduction capacity of gray water reclamation systems was theoretically estimated considering the use of gray water from laundry, showers, and washing basins followed by an on-site treatment of gray water for toilet flushing. The theoretical concept and design of the on-site gray water reclamation systems in this study was based on the following criteria: (i) segregated gray water gravity sewers; (ii) on-site gray water treatment without electricity consumption in vertical flow constructed wetlands; (iii) treated gray water stored in an underground tank; (iv) indirect gravity supply using header tanks; (v) pumping from storage tank to header tank; and (vi) UV disinfection to treat gray water stored at header tank. The footprint of constructed wetlands for each studied household was calculated using Equation (7):

\[
F_w = \frac{G_{sew} \times T_h \times (1 + p - et)}{V \times H} \quad (7)
\]

where \(F_w\) is the footprint of the constructed wetland (m²); \(G_{sew}\) is the generation of sewage from gray water streams (L/day); \(T_h\) is the hydraulic retention time (day); \(p\) is the fraction of water added to the system due to precipitation (dimensionless); \(et\) is the fraction of water losses due to evapotranspiration (dimensionless); \(V\) is the fraction of void volume and pore space of the filter medium (dimensionless); and \(H\) is the depth of the wetland discounting the freeboard (mm).

The depth of the wetlands and the fraction of void volume and pore space were assumed to be equal to 500 mm and 40%, respectively. In a conservative way, the adopted retention time of gray water in the constructed wetlands was two days. The sewage treatment capacity achieved by on-site gray water reclamation systems was estimated using Equation (8):

\[
G_{sew} = \sum_{i=1}^{n} g_n \quad (8)
\]

where \(G_{sew}\) is the generation of sewage from gray water streams (L/day); \(g_n\) is the raw gray water generation of a sewage source point (L/day); and \(n\) is the number of sewage source points.

The treated gray water supply capacity after water gains and losses was calculated for each household using Equation (9). The water gains from rainfall precipitation, 5% on average, were calculated through an iterative process considering the footprint of the wetlands and the rainfall precipitation pattern in Florianópolis. On the other hand, water losses due to evapotranspiration, 10% on average, were assumed to be equal to values described by Headley et al. (2012) for a sub-tropical region in Australia with a similar climate to Florianópolis.

\[
G_{sup} = G_{sew} \times (1 + p - et) \quad (9)
\]

where \(G_{sup}\) is the average supply capacity of treated gray water (L/day); \(G_{sew}\) is the generation of sewage from gray water streams (L/day); \(p\) is the fraction of water added to the system due to precipitation (dimensionless); and \(et\) is the fraction of water losses due to evapotranspiration (dimensionless).

For each studied household, the potential water service provision using treated gray water was defined as the average supply capacity, when gray water demand was greater than the supply capacity; and as equal to the average gray water demand, when the supply capacity exceeded the demand. The potential sewerage service provision of on-site gray water treatment systems was equal to the generation of sewage from gray water streams. This is because systems were designed to treat all the gray water generated on-site and surplus treated gray water was considered to be disposed of on-site in soakage trenches.

**Rainwater harvesting systems**

The supply capacity of rainwater harvesting systems was estimated through computer models performed in the
computer program Netuno 4.0. Rainwater supply was disregarded for end uses other than toilet flushing and laundry due to the negligible use of water for irrigation and other external end uses at the studied households, as well as water quality constraints on supplying most of the indoor end uses. The theoretical concept and design of studied on-site rainwater harvesting systems was based on: (i) rainwater collection from roof catchments; (ii) treatment using first flush diverters; (iii) storage in ground-level tank; (iv) indirect gravity supply using header tank; (v) pumping from storage tank to header tank; and (vi) UV disinfection for rainwater at header tank.

The input data of models for each household included: (i) daily rainfall data for the last decade in Florianópolis (January 2002 to December 2011) obtained from the National Institute of Meteorology; (ii) roof catchment area measured on-site; (iii) total water demand measured on-site; (iv) end uses suitable for rainwater supply measured on-site; (v) rainwater runoff coefficient based on a literature review and roof materials obtained on-site; (vi) header tank capacity equal to volume multiple of 100 L immediately above the daily rainwater demand estimated from water end uses measured on-site; and (vii) first flush diversion height equal to 2 mm as per the Brazilian Rainwater Plumbing code – NBR 15.527 (ABNT 2007). Moreover, the ideal storage volume for the ground-level rainwater tank was estimated for capacities ranging from 0 to 10 m³ in 0.5 m³ intervals.

The supply capacity and ideal storage capacity of rainwater harvesting systems were determined as the capacities in which the potential supply capacity of rainwater increased less than 2% per m³ in relation to the supply capacity achieved with the storage capacity immediately above.

**Energy consumption of water and sewerage services**

The energy consumption of water and sewerage services will likely have a spiralling trend due to population growth and associated expansion of demand and energy intensity to provide water and sewerage services. Such variables were taken into account in Equation (10) so as to estimate the energy consumption during the studied planning horizon. The growth, throughout the planning horizon, of each variable in Equation (10) was taken into account.

\[
E_n = \sum_{i=0}^{n} IE_i \times P_i \times D_i \times S_i
\]

where \(E_n\) is the energy consumption for service provision in the planning horizon (kWh); \(IE_i\) is the energy intensity of the strategy for service provision in the year ‘i’ (kWh/m³); \(P_i\) is the population in the year ‘i’ (people); \(D_i\) is the average water demand in the year ‘i’ (m³/(capita·year)); \(S_i\) is the service coverage in the year ‘i’ (dimensionless); \(n\) is the number of years in the planning horizon.

The energy-saving potential of each strategy was estimated by comparing their respective energy consumption with the energy consumption of conventional centralized water and sewerage services.

**RESULTS AND DISCUSSION**

**Energy intensity of centralized water and sewerage services**

The average energy intensity of the empirical data for centralized water and sewerage services over 2004–2010 in Florianópolis was equal to 0.38 and 0.57 kWh/m³, respectively. The energy intensity of centralized water services presented a declining trend throughout this time, with an average of 0.21 kWh/m³ for the planning horizon. This increase may indicate improvements in the operation of water supply systems in recent years (e.g. pressure and leakage management, and energy efficiency initiatives for pumping systems), and is likely to persist in the future due to continuous improvement measures and higher efficiency of infrastructure augmentations.

The energy intensity of sewerage services fluctuated from 2004 to 2010. This variation may be attributed to the influence of parameters which vary randomly over time (e.g. rainfall). Therefore, there was assumed to be a steady trend for the energy intensity of sewerage services equal to 0.57 kWh/m³ throughout the planning horizon.
Energy intensity of integrated on-site water and sewerage services

The total average energy intensity for gray water reclamation or rainwater harvesting systems varied from 0.25 to 0.88 kWh/m³ for the 20-year planning horizon (Table 1). The energy efficiency of the systems was optimized by using indirect water distribution systems with the use of header tanks in order to reduce the number of pump startups. Furthermore, the most energy-efficient pumps, the ideal UV reactor diameter and lamp power rating were selected to achieve high energy efficiency levels. Moreover, throughout the planning horizon, enhancements in the energy performance of alternative water supply systems were considered, including: 50% reduction in energy requirement for standby power in pumping and disinfection systems; elimination of maximum UV output time lapse; and 80% improvement in the conversion of electricity into UV radiation by replacing fluorescent lamps with LED ones.

The highest energy intensity, 0.88 kWh/m³, was calculated for on-site alternative water supply systems with the lowest water consumption pattern (i.e. 100 L/day). The low demand of water led to excessive energy consumption for standby operation in pumping and disinfection systems. The energy intensity decreased with an increase of alternative water consumption, in which the lowest calculated energy intensity, i.e. 0.25 kWh/m³, was reached for alternative supplies with water consumption equal to 600 L/day. The energy consumption for pumping and UV disinfection operations followed a similar trend due to their equivalent energy consumption for standby mode, which corresponds to a considerable portion of the total energy intensity in energy-efficient on-site alternative water supply systems in buildings with low water consumption patterns (e.g. single-family detached houses). Thus, the energy intensity of energy-efficient alternative water and sewerage systems is a function of the water consumption patterns of households. The higher the alternative water consumption, the less will be the energy intensity to provide on-site water and sewerage services.

Water consumption pattern and end-use analysis

The water consumption analysis revealed that the studied households consumed 123 L/capita·day on average, from which 25%, 25%, and 27% were used for toilet flushing, clothes washing, and showering, respectively (Table 2). Thus, such end uses correspond to most (77% on average) of the total water consumption and sewage production, and hence should be targeted in integrated water and sewage management strategies for the studied sample. Nonetheless, the contribution of each end use varied considerably among the households, which indicates the necessity of tailored site-specific strategies depending on the water consumption and sewage production patterns.

Non-potable water end-uses which can be supplied by rainwater accounted for 24–70% of total water consumption in households, with an average of 52%. Gray water supply demand, equivalent to the water consumption for toilet flushing, ranged from 10% to 44% of the total consumption pattern, with an average of 25%. Gray water effluent generation from showers, washing machines, laundry troughs, and bathroom washing basins were equivalent to 58% of the total sewage of households, varying from 34% to 80%.

Table 1: Average energy intensity of optimized on-site alternative water supply systems for single-family detached houses and centralized water and sewerage services during the planning horizon (2010–2030)

<table>
<thead>
<tr>
<th>Alternative water consumption pattern (L/day)</th>
<th>Energy intensity (kWh/m³)</th>
<th>On-site pumping</th>
<th>On-site UV disinfection</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.44</td>
<td>0.44</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>0.25</td>
<td>0.25</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>0.18</td>
<td>0.19</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>0.15</td>
<td>0.16</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.13</td>
<td>0.15</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>0.12</td>
<td>0.13</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Centralized water services</td>
<td>–</td>
<td>–</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>Centralized sewerage services</td>
<td>–</td>
<td>–</td>
<td>0.21</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Water consumption pattern and end uses in low-income households in Florianópolis, Brazil

<table>
<thead>
<tr>
<th>Non-potable end uses (%)</th>
<th>Potable end uses (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toilet</td>
<td>Washing machine</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>
Integrated water and sewage management strategies

Gray water reclamation systems

The potential of gray water reclamation systems to provide water and sewerage services was equivalent to the total water demand for toilet flushing and the supply capacity of gray water, respectively, ranging from 10% to 40% and from 34% to 80% to provide water and sewerage services, respectively (Table 3).

Rainwater harvesting systems

The supply capacity of the designed rainwater harvesting systems ranged from 22% to 64% of the total water consumption of the assessed households, with an average of 43% (Table 4).

Comparison of strategies

Rainwater harvesting systems achieved the greatest potential to provide water services (43%), followed by gray water reclamation systems (24%). Gray water reclamation systems had the potential to reduce the reliance on centralized sewerage services (58% on average), while rainwater harvesting systems had no impact on the operation of sewerage systems. The different potential obtained for water and sewerage service provision among strategies is a function of the water end-uses supplied by alternative water sources and the gray water streams treated on-site in comparison with the total water and sewerage services demand (Table 5).

Energy intensity

The average energy intensity of centralized water and sewerage services was equal to 0.84 kWh/m³ throughout the planning horizon (Table 6). With the use of gray water reclamation, the energy intensity of water and sewerage services could be reduced to levels varying from 0.41 to 0.66 kWh/m³, with an average of 0.54 kWh/m³. By contrast, the use of rainwater harvesting systems prompted an increase in the energy intensity, reaching a higher energy intensity than the combination of centralized water and sewerage systems (i.e. 0.86 kWh/m³ on average, ranging from 0.82 to 0.92 kWh/m³).

The energy intensity levels reported herein are comparable to those in other studies (e.g. 0.40 to 0.8 kWh/m³ for gray water constructed wetland (Winward et al. 2008) and 0.90 kWh/m³ minimum energy intensity of rainwater harvesting systems (Retamal et al. 2009)).

Potential energy savings on a city scale

The energy consumption of all studied strategies increased over time due to population growth and increased coverage of sewerage systems. The energy consumption of centralized water and sewerage services was equal to 164 GWh during reclamation systems (24%). Gray water reclamation systems had the potential to reduce the reliance on centralized sewerage services (58% on average), while rainwater harvesting systems had no impact on the operation of sewerage systems. The different potential obtained for water and sewerage service provision among strategies is a function of the water end-uses supplied by alternative water sources and the gray water streams treated on-site in comparison with the total water and sewerage services demand (Table 5).

Energy intensity

The average energy intensity of centralized water and sewerage services was equal to 0.84 kWh/m³ throughout the planning horizon (Table 6). With the use of gray water reclamation, the energy intensity of water and sewerage services could be reduced to levels varying from 0.41 to 0.66 kWh/m³, with an average of 0.54 kWh/m³. By contrast, the use of rainwater harvesting systems prompted an increase in the energy intensity, reaching a higher energy intensity than the combination of centralized water and sewerage systems (i.e. 0.86 kWh/m³ on average, ranging from 0.82 to 0.92 kWh/m³).

The energy intensity levels reported herein are comparable to those in other studies (e.g. 0.40 to 0.8 kWh/m³ for gray water constructed wetland (Winward et al. 2008) and 0.90 kWh/m³ minimum energy intensity of rainwater harvesting systems (Retamal et al. 2009)).

Potential energy savings on a city scale

The energy consumption of all studied strategies increased over time due to population growth and increased coverage of sewerage systems. The energy consumption of centralized water and sewerage services was equal to 164 GWh during

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### Table 3 | Performance of gray water reclamation systems amongst the 10 houses

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water consumption (L/capita-day)</td>
<td>70.3</td>
<td>122.9</td>
<td>194.8</td>
</tr>
<tr>
<td>Supply capacity (%)</td>
<td>32</td>
<td>56</td>
<td>76</td>
</tr>
<tr>
<td>Gray water production (L/day)</td>
<td>103.3</td>
<td>223.5</td>
<td>558.3</td>
</tr>
<tr>
<td>System footprint (m²)</td>
<td>1.0</td>
<td>2.2</td>
<td>5.6</td>
</tr>
<tr>
<td>Gray water end-uses (%)</td>
<td>10</td>
<td>25</td>
<td>44</td>
</tr>
<tr>
<td>Treated gray water demand (%)</td>
<td>13</td>
<td>49</td>
<td>100</td>
</tr>
<tr>
<td>Capacity to meet water service (%)</td>
<td>34</td>
<td>58</td>
<td>80</td>
</tr>
<tr>
<td>Capacity to meet sewerage service (%)</td>
<td>103.3</td>
<td>223.5</td>
<td>558.3</td>
</tr>
</tbody>
</table>

### Table 4 | Performance of rainwater harvesting systems amongst the 10 houses

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water consumption (L/capita-day)</td>
<td>70.3</td>
<td>122.9</td>
<td>194.8</td>
</tr>
<tr>
<td>Roof catchment area (m²)</td>
<td>56</td>
<td>87</td>
<td>122</td>
</tr>
<tr>
<td>Average runoff coefficient</td>
<td>0.73</td>
<td>0.78</td>
<td>0.90</td>
</tr>
<tr>
<td>Rainwater end uses (%)</td>
<td>24</td>
<td>52</td>
<td>70</td>
</tr>
<tr>
<td>Ideal rainwater storage capacity (L)</td>
<td>1,500</td>
<td>3,100</td>
<td>4,000</td>
</tr>
<tr>
<td>Ideal header tank capacity (L)</td>
<td>100</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>Capacity to meet water service (%)</td>
<td>22</td>
<td>43</td>
<td>64</td>
</tr>
</tbody>
</table>

### Table 5 | Performance of integrated water and sewage management strategies in all studied households

<table>
<thead>
<tr>
<th>Service</th>
<th>Strategy</th>
<th>On-site provision (%)</th>
<th>Centralized system (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Gray water</td>
<td>24</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>Rainwater</td>
<td>43</td>
<td>57</td>
</tr>
<tr>
<td>Sewerage</td>
<td>Gray water</td>
<td>58</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Rainwater</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>
the planning horizon, with an average of 8.2 GWh/year. The use of rainwater harvesting systems showed the highest energy consumption among the studied strategies during the planning horizon (171 GWh or 8.5 GWh/year on average). The energy consumption of this strategy could be even higher by considering standard rainwater harvesting systems without the energy efficiency optimization proposed herein (Vieira et al. 2014). The use of gray water reclamation promoted a reduction of 31% in the energy consumption of centralized systems, i.e. 113 GWh or 5.6 GWh/year. The enhanced energy performance of gray water systems in comparison with rainwater and centralized water and sewerage services is mostly related to their capacity to reduce both the total amount of sewage discharged into centralized systems, and their capacity to treat gray water streams at a low energy intensity in constructed on-site wetlands with low electricity demand.

**CONCLUSION**

In conclusion, from an energy management viewpoint, the sustainability of the water sector is primarily related to the reduction of effluent to centralized systems rather than the use of alternative water sources. Taking into account the increasing coverage of sewerage services in Florianópolis, energy consumption in the water sector will increase due to the increased volume of sewage collected and treated. Therefore, to mitigate the impacts related to an increase of energy consumption in the water sector in Florianópolis, strategies that incorporate measures to minimize sewage production in low-income households ought to be adopted.

### REFERENCES


PMF 2010 *Plano Municipal Integrado de Saneamento Brasico – Florianópolis (Integrated Sanitation Plan of Florianópolis).*

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**Table 6** | Average energy intensity among the different measures within the studied strategies for water and sewerage service provision between 2010 and 2030

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Energy intensity (kWh/m³)</th>
<th>Year 2010</th>
<th>Year 2030</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Water</td>
<td>Sewerage</td>
<td>Water</td>
</tr>
<tr>
<td>Centralized</td>
<td></td>
<td>0.27</td>
<td>0.57</td>
<td>0.17</td>
</tr>
<tr>
<td>Gray water</td>
<td></td>
<td>0.37</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>Rainwater</td>
<td></td>
<td>0.36</td>
<td>0.57</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Note: The water services are a combination of centralized and alternative water sources at sites with either gray water or rainwater use.
Secretaria Municipal de Habitação e Saneamento Ambiental (SMHSA) (Municipal Directorate of Housing and Sanitation), Florianópolis City Council. Florianópolis, SC, Brazil.


First received 3 June 2015; accepted in revised form 20 August 2015. Available online 3 September 2015