Domestic Water End-Uses and Water Conservation in Multi-Storey Buildings in the Federal District, Brazil

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ABSTRACT: In order to evaluate the effectiveness of demand-side and supply-side water conservation measures and identify viable solutions to reduce domestic water consumption, it is crucial to quantify how much water is consumed by each major domestic water fixtures and appliances and understand how water is being used by residents in a household. Having these issues in mind, the overall aim of this investigation was to provide specific information regarding domestic water end-use consumption and assess the feasibility for an array of water conservation equipments and systems in terms of their applicability, water savings and financial benefits for residential multi-storey buildings in the Federal District, Brazil. Findings suggest that low budget water efficient equipments are of simple installation and are capable of promoting water savings and financial benefits. Although water reuse systems were capable of promoting significant reductions on water consumption, overall, they proved to be economically unviable options due to their high costs, suggesting that governmental policies and subsidies over taxes and interest rates could be used as means of promoting incentives for the general public to invest in water reuse systems.

Keywords: water end-uses, water efficiency, water reuse, cost-benefit analysis, adaptation

INTRODUCTION
The detailed understanding of domestic water end-use consumption patterns makes way to both development and evaluation of water demand management programs. The study of domestic water end-use consumption is crucial to achieve a more accurate forecast of water demand. Quantifying the amount of water consumed by each individual water fixture and appliance in the home allows us to accurately identify consumption ‘hot-spots’ and the uses that offer the greatest conservation potential. Furthermore, the clear understanding of domestic water end-use consumption can help identify optimal water conservation measures for an improved efficiency and effective water demand management.

The characterization of domestic water end-use consumption has led to a series of investigations that have evaluated the potential water savings [1-4] and the economics of a range of domestic water conservation measures in developed nations [5-11]. These countries, however, present a socioeconomic reality different from that found in developing countries. Little is known about the feasibility of domestic water conservation measures in developing economies. In Brazil, water conservation studies have focused in estimating the reductions promoted by leakage repair [12] and use of flow regulators [13] in multi-storey residential buildings, through the installation of water efficient equipments in low income houses [14], and rainwater harvesting and greywater recycling systems in southern Brazil [15-19]. Some studies have verified the payback period of rainwater and greywater reuse systems separately and in combination for two houses and three multi-storey residential buildings in southern Brazil [17, 18]. Another, evaluated the viability of rainwater harvesting using net present value linked with public awareness and acceptance of the use of rainwater for homes in north-eastern Brazil [20]. The overall aim of this investigation was to assess domestic water end-use consumption and identify the feasibility for an array of water conservation equipments and systems in terms of their applicability, water savings and financial benefits for residential multi-storey buildings in the Federal District, Brazil.

METHODOLOGICAL APPROACH
In order to address these objectives, statistically representative sites were selected based on secondary sources of statistical data obtained from Government’s Household District Survey [21]. From 27 Administrative Regions in the Federal District, Brasilia and Águas Claras Administrative Regions were selected for primary data collection mainly because these regions are comprised of residential multi-storey buildings.

A distinction between indoor and outdoor water consumption was necessary for data collection. Due to typological characteristics, residential multi-storey buildings in the Federal District contain communal grounds and gardens which lead to a collective water consumption for floor washing and irrigation, an activity usually done by cleaners and gardeners during maintenance. Although most residential multi-storey
buildings contain one water meter to measure water consumption for the entire building block, some buildings possess a distinct water meter solely to measure outdoor water consumption. In this case, 30 buildings containing this extra water meter were selected for the analysis of outdoor water end-use consumption. As a starting point, a structured interview directed to building managers was used in order to collect primary data regarding building characteristics, frequency, habits and equipments used for floor washing and irrigation. During the interview, water bills were collected for the past twelve months. Floor, garden and roof areas as well as plumbing configuration were obtained from architecture and plumbing plans (if available) or through an in-situ survey. Outdoor water end-use consumption was estimated according to measured flow rates and timed data of water usage (Equation 1). Flow rates of external taps and fixtures (such as garden hose with nozzles and pressure washers) were identified by measuring the time it took to fill up a ten litre bucket during its operation. Water flow from external taps and fixtures was timed during water use events as they took place by observing users during one of their routine activities of floor washing and irrigation.

An in-depth analysis of indoor water end-use consumption was carried out through the use of a questionnaire survey and a water auditing technique developed, to estimate, for seven days, domestic water end-use consumption for 19 flat dwellings in Brasilia and 16 flat dwellings in Águas Claras. Face-to-face questionnaires were applied to residents prior water auditing to collect primary data on dwelling characteristics, public opinion, awareness and acceptance of water conservation measures and their water-using habits. To measure indoor water end-use consumption, one stop-watch was fixed next to each water fixture so that residents could easily register the time a fixture was used, by pressing a button to start and pause the timer. This stop-watch technique proved to be an effective, user friendly method for time-tracking water use events, and it was capable of storing the timed data. Due to the fact that toilets, washing machines and dishwashers present a fixed rate of water consumption, a diary-tracking technique was used. Residents were asked to record the number of toilets flushed using diary cards fixed to the wall next to each toilet. As for washing machines and dishwashers, residents were asked to record the day, number of uses and indicate the programme selected. In order to obtain daily domestic water end-use consumption for a period of seven days, one resident was asked to enter the number of ticks from toilet flushing, clothes washing, dish washing and register the accumulated consumption time of every fixture at a daily summary card, and reset all stop-watches for the next day.

A full inventory of appliances, fixtures and other water-consuming features was carried out in order to identify sources of water usage, quantify their flow rates and detect any visible leaks. The flow rate of every tap-opening fixture was identified by measuring the time it took to fill up a one litre container by opening the tap half a turn in order to obtain the average flow of a tap, thus obtaining its flow rate. Flow rates of toilets were estimated according to the basin’s flushing volume. Water usage from washing machines and dishwashers were obtained from manufacturers’ data sheets according to programme settings. Based on the measured fixture flow rates and the timed data of water end-uses collected during domestic water auditing, it was possible to identify the volume of water consumed daily per tap-opening fixture (Equation 1). However, in order to obtain daily water consumption figures from appliances such as toilets, washing machines and dishwashers, appliance consumption rates per use were multiplied by the number of uses recorded by residents during the domestic water audits (Equation 2).

\[ D_f = \frac{[(hr \times 3600) + (min \times 60) + sec]}{Q_f} \times Q_f \] (1)

\[ D_a = N \times Q_a \] (2)

In order to identify feasible water conservation measures in terms of their applicability, water savings and financial benefits, a representative model was created according to the values of primary data collected from fieldwork survey. Input data such as baseline water end-use consumption, number of residents, built area, garden/yard area, roof area, number of fixtures and appliances and their measured flow rates, were used to calculate domestic water reductions of water efficient equipments and water reuse systems. The representative models were also used as a basis to estimate capital costs and evaluate the applicability of water conservation measures in terms of building adaptation. Therefore, typological characteristics of dwellings were considered for analysis. Input data regarding public opinion, level of acceptance and the willingness-to-pay for water conservation strategies, were applied to the models in order to evaluate their applicability.

For this study, only commercially available water efficient equipments in Brazil were considered for analysis. These included, flow restrictors for lavatory, kitchen and utility faucets, automatic lavatory faucet, lavatory sensor faucet, kitchen sensor faucet, low-flow shower head, low-flush toilet, dual-flush toilet, high-efficiency washing machine, automatic shut-off hose.
nozzle, pressure washer and automatic irrigation system. Overall, water savings for these strategies were determined according to their potential water savings, reduced flow rates or consumption loads. In order to analyse the potential water savings from rainwater harvesting systems, three types of non-potable demands were considered for analysis: (Reuse 1) irrigation and floor washing; (Reuse 2) irrigation, floor washing and toilet flushing; and (Reuse 3) irrigation, floor washing, toilet flushing and clothes washing. For each of the above rainwater demands, simulations based on daily time intervals using the behavioural model in Equation 3 with a yield after spillage operating rule (Equation 4) for a series of storage volumes was carried out in order to identify water savings for an array of rainwater tank sizes.

\[
V_t = V_{t-1} + S_t - D_t \tag{3}
\]

Subject to \(0 \leq V_{t-1} \leq C\)

\[
V_t = \text{Storage volume at time interval, } t
\]

\[
V_{t-1} = \text{Storage volume at time interval, } t-1
\]

\[
S_t = \text{Supply during time interval, } t
\]

\[
D_t = \text{Demand during time interval, } t
\]

\[
C = \text{Storage capacity}
\]

\[
Y_t = \min \left\{ \frac{D_t}{V_{t-1} + S_t}, \frac{V_{t-1} + S_t - Y_t}{C} \right\} \tag{4}
\]

\[
Y_t = \text{Yield during time interval, } t
\]

A water reduction index was used as an indicator to compare the level of potable water reductions promoted by different types of water-saving strategies individually or in combination (Equation 5).

\[
WRI = \left( \frac{D_{base} - D_{red}}{D_{base}} \right) \times 100 \tag{5}
\]

\[WRI = \text{Water reduction index (\%)}
\]

\[D_{base} = \text{Baseline water consumption (m}^3\text{)}
\]

\[D_{red} = \text{Reduced water consumption (m}^3\text{)}
\]

In order to appraise the financial benefits for a comprehensive range of water conservation measures of different scales and lifespan, an average incremental cost-benefit analysis was used in order to compare the cost effectiveness of large initiatives with that of smaller ones by scaling net present value of a series of incurred future capital and operational costs for each measure as a rate of financial benefit in Brazilian Real per volume of water saved in cubic meters (R$/m^3) within the same time horizon (Equation 6). Given the fact that water reuse systems contained the oldest average life expectancy equivalent to 30 years, such time horizon was used for analysis. A 3% discount rate was estimated according to the average values of reference interest rates and long term interest rates from June 2009 to June 2010, obtained from Brazil’s Central Bank.

\[
AIC = - \left[ \frac{K - B + C_o}{\sigma_w} \right] \tag{6}
\]

\[AIC = \text{Average incremental cost (R$/m}^3\text{)}
\]

\[K = \text{Net present value of capital costs (R$)}
\]

\[B = \text{Net present value of benefits (R$)}
\]

\[C_o = \text{Net present value of operational costs (R$)}
\]

\[\sigma_w = \text{Total water savings (m}^3\text{)}
\]

**DWELLING CHARACTERISTICS**

All of Brasília’s and Águas Claras’ dwellings were flats, with a mean built area of 91m². Brasília and Águas Claras residential multi-storey buildings differed in size and built form. Brasília’s residential building stock consisted of dominantly horizontal buildings of 4 or 6 storeys with 8 to 6 flats per floor and a mean roof area of 1,095m². Águas Claras’ residential building stock was dominantly vertical buildings ranging from 12 to 25 storeys high with 4 flats per floor and a mean roof area of 434m². Building blocks for both Brasilia and Águas Claras contained a mean 1,164m² of communal grounds. The analysed dwellings presented an average of 5 residents with a mean household income of 20.3
minimum wages (R$12,626.60). Most of the respondents were outright owners of their homes (71%), and 83.7% would be willing to adapt their dwelling for water conservation. Those willing to retrofit their dwellings for water conservation, most would make monthly investments between R$11.00 and R$50.00 for 6 to 12 months. Table 1 below shows the average number of water using fixtures and appliances per dwelling and their measured flow rates. Although no leaks were detected, the great majority of dwellings (86.6%) did not contain any type of water efficient equipment.

**DOMESTIC WATER END-USES**

With a mean indoor water consumption of 237 m³ per dwelling per year (m³/dw/yr) and a mean per capita consumption equivalent to 221 litres per person per day (l/p/d), indoor water-consuming activities from shower heads (23.9%), washing machines (22.1%), toilet flushes (15.8%) and kitchen faucets (15.5%) had the highest rates of daily water consumption per person, while dishwashers (0.7%), water filters (1.3%) and bidet/hand douches (1.5%) contained the lowest rates of daily consumption per person (Table 1).

**Table 1: Domestic water end-use consumption.**

<table>
<thead>
<tr>
<th>Fixtures &amp; Appliances</th>
<th>Flow Rate</th>
<th>Frequency</th>
<th>Water Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathroom Faucet (3)</td>
<td>6.7 l/min</td>
<td>3.1 min*</td>
<td>21 l/p/d</td>
</tr>
<tr>
<td>Shower Head (3)</td>
<td>5.7 l/min</td>
<td>9.2 min*</td>
<td>53 l/p/d</td>
</tr>
<tr>
<td>Bidet / Hand Douche (2)</td>
<td>7.2 l/min</td>
<td>0.5 min*</td>
<td>3 l/p/d</td>
</tr>
<tr>
<td>Toilet Flush (3)</td>
<td>9 l/flush</td>
<td>4 flushes*</td>
<td>35 l/p/d</td>
</tr>
<tr>
<td>Kitchen Faucet (1)</td>
<td>6.8 l/min</td>
<td>5.1 min*</td>
<td>34 l/p/d</td>
</tr>
<tr>
<td>Water Filter (1)</td>
<td>2.2 l/min</td>
<td>1.2 min*</td>
<td>3 l/p/d</td>
</tr>
<tr>
<td>Dishwasher (1)</td>
<td>12.6 l/load</td>
<td>0.1 load*</td>
<td>1 l/p/d</td>
</tr>
<tr>
<td>Utility Faucet (1)</td>
<td>7.4 l/min</td>
<td>2.9 min*</td>
<td>22 l/p/d</td>
</tr>
<tr>
<td>Washing Machine (1)</td>
<td>164 l/load</td>
<td>0.3 load*</td>
<td>49 l/p/d</td>
</tr>
<tr>
<td>External Tap (3)</td>
<td>16.8 l/min</td>
<td>0.03 min**</td>
<td>0.5 l/m²/d</td>
</tr>
</tbody>
</table>

*Average number of fixture or appliance per dwelling in parenthesis
* person per day  **m² per day

Irrigable garden areas, as well as paved yards and other washable floor areas were considered as a basis for parametrical comparison of outdoor water consumption in litres per area per day (l/m²/d). Mean outdoor water consumption was equivalent to 0.5 l/m²/d. Monthly variations of mean outdoor water consumption throughout the year were analysed by cross-referencing secondary climatic data of monthly relative humidity. It was observed that outdoor water consumption had a direct relationship with relative humidity, where the lower the relative humidity, the higher the outdoor water consumption, and the higher the relative humidity, the lower outdoor water consumption was (Fig. 1). During the rainy season, 90.9% of the communal gardens were rain-fed only and a mean base load of 7 m³/month for floor washing could be observed. During the dry season, however, an additional mean consumption of 21 m³/month for irrigation could be observed.

**BUILDING ADAPTATION**

Overall, dwelling retrofit for water efficient equipments proved to be of simple installation, requiring little or no refurbishment for their application. Water reuse systems on the other hand, required some level of building adaptation. Since mains water distribution to outdoor end-uses in Brazil is commonly directly fed from the incoming service pipe, treated rainwater distribution to outdoor end-uses such as irrigation and floor washing proved to be a simple, low budget scheme that could be either adapted to the existing pipework or be installed separately, avoiding cross-connections between potable and non-potable water. On the other hand, indoor water-end-uses in Brazilian dwellings are indirectly fed via a header water tank located at the building’s loft. In this case, the installation of a new distribution pipework destined for non-potable end-uses would require a high level of investment for refurbishment of the existing network. Thus, such retrofitting option proved to be unfeasible and was considered to be extremely inconvenient to residents. However, some plumbing configurations presented a separate distribution pipework designated solely for toilet flushing or laundry (washing machine and utility faucet). A simple and effective way of adapting existing dwellings for non-potable indoor water reuse could be derived by simply modifying the existing header pipework layout at loft level. Such adaptation proved to be of low cost, rendering in little inconvenience to residents.

Every building block analysed contained a rainwater collection network which could be easily adapted for rainwater harvesting. This could be done at ground level, either by diverting a section of the existing collection pipes, or through the use of a diversion chamber, to separate the necessary run-off volume to an underground storage tank located in the proximity of the building.
Overall, a major adaptation to existing bathroom wastewater drainage pipework to collect greywater from showers and lavatories would be necessary, and this proved to be an unviable option due to high costs of refurbishment and inconvenience to residents. However, most laundry wastewater pipework contained a segregated stack pipe for vertical drainage that only met discharge pipes at an inspection chamber at ground level. Such configuration could be easily adapted before the pipes reach the inspection chamber by diverting laundry greywater to treatment. Wastewater collection for multi-storey buildings would require little refurbishment to their existing wastewater discharge network, since wastewater reclamation systems treat both greywater and black water for reuse.

WATER SAVINGS
Domestic water savings were estimated for every water conservation measure. Overall, high-efficiency washing machines proved to be the most effective water efficient strategy, with an average rate of potable water savings equivalent to 29 m³/dw/yr, followed by dual flush toilets (22 m³/dw/yr) and bathroom faucet flow regulators (17 m³/dw/yr). Automatic irrigation system (0.3 m³/dw/yr), pressure washers (1.7 m³/dw/yr) and utility faucet flow regulators (4.4 m³/dw/yr), contained the lowest level of annual water reductions. Table 2 on the next page shows the water reduction index from different water efficient fittings, fixtures and appliances. Individually, potential water reductions for water efficient equipments ranged from 1.1% to 23.6% of total dwelling consumption. In combination, water efficient equipments were capable of promoting water reductions up to 42.3% of baseline water consumption. Such reduced scenario was considered in estimating potential water reductions for water reuse systems.

Figure 2: Cumulative supply vs. cumulative demands.

Annual water savings of different rainwater storage volumes for the different types of rainwater demands (Reuse 1, Reuse 2 and Reuse 3) were estimated according to both baseline and reduced water end-use consumption scenarios. Rainwater harvesting systems destined to supply communal outdoor end-uses (Reuse 1) proved to be a more feasible option than to supply indoor end-uses. Apart from rainwater Reuse 2 in a reduced scenario, findings indicated that multi-story buildings contained insufficient roof area to adequately supply such intense indoor demands. Figure 2 demonstrates this graphically, through a mass curve analysis of cumulative rainwater supply and cumulative rainwater demands. Results from simulations based on daily time intervals revealed that due to the extreme indoor demand, on the end of the day, the rainwater tank would always be empty, independent of its storage volume.

Figure 3: Annual water savings per rainwater storage volumes.

Figure 3 shows the behaviour of annual water savings per rainwater storage volume. It was observed that, at first, annual water savings rose proportionally to the increase in rainwater storage volume, however, water savings stagnated once the rainwater harvesting system achieved its maximum capacity to promote domestic water reductions, independent of the increase in storage volume. Rainwater harvesting systems for Baseline Demand 2, Baseline Demand 3 and Reduced Demand 3 made use of the buildings’ full potential to collect rainwater, generating a fixed annual water saving of 1,332 m³/yr, independent of storage volume. Overall, greywater recycling systems provided higher annual water savings at a baseline scenario than in a reduced water consumption scenario. At a baseline level, water savings were equivalent to 3 m³/dw/yr (Reuse 1); 39 m³/dw/yr (Reuse 2) and 65 m³/dw/yr (Reuse 3). In a reduced scenario, water savings were equivalent to 1 m³/dw/yr (Reuse 1); 17 m³/dw/yr (Reuse 2); and 60 m³/dw/yr (Reuse 3). Similarly, wastewater reclamation systems presented higher water savings at a baseline scenario equivalent to 3 m³/dw/yr (Reuse 1) and 41 m³/dw/yr (Reuse 2). At a reduced scenario water savings were 0.6 m³/dw/yr (Reuse 1) and 17 m³/dw/yr (Reuse 2).
COST-BENEFIT ANALYSIS
An average incremental cost-benefit analysis was used to compare the cost effectiveness of the applicable water conservation measures with different life expectancies using a time horizon of 30 years. The economic assessment indicated that water efficient equipments presented a higher financial return per cubic meter of water saved than water reuse systems. Table 2 summarizes findings indicating viable water conservation measures in terms of their water savings and cost-benefits to adapt residential multi-storey buildings in the Federal District, Brazil.

Table 2: Water reduction index (WRI) and average incremental cost (AIC) of viable water conservation measures.

<table>
<thead>
<tr>
<th>WATER CONSERVATION MEASURES</th>
<th>WRI (%)</th>
<th>AIC (R$/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Efficient Water Technologies</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficient Washing Machine (76 l/load)</td>
<td>11.7</td>
<td>7.29</td>
</tr>
<tr>
<td>Bathroom Faucet Flow Regulator (1.8 l/min)</td>
<td>6.9</td>
<td>2.69</td>
</tr>
<tr>
<td>Low-Flow Shower Head (4.5 l/min)</td>
<td>5.0</td>
<td>2.66</td>
</tr>
<tr>
<td>Low-Flush Toilet (6 lpf)</td>
<td>5.2</td>
<td>1.68</td>
</tr>
<tr>
<td>Dual Flush Toilet (3/6 lpf)</td>
<td>9.0</td>
<td>0.37</td>
</tr>
<tr>
<td>Kitchen Sensor Faucet</td>
<td>6.1</td>
<td>0.20</td>
</tr>
<tr>
<td>Kitchen Faucet Flow Regulator (1.8 l/min)</td>
<td>4.1</td>
<td>2.75</td>
</tr>
<tr>
<td>Utility Faucet Flow Regulator (6 l/min)</td>
<td>1.8</td>
<td>2.60</td>
</tr>
<tr>
<td>Pressure Washer</td>
<td>0.7</td>
<td>2.87</td>
</tr>
<tr>
<td>Automatic Irrigation Sprinkler System</td>
<td>0.1</td>
<td>0.57</td>
</tr>
<tr>
<td><strong>Rainwater Harvesting (RWH) for Baseline Consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RWH System 1m³ Tank - Reuse 1</td>
<td>0.7</td>
<td>1.11</td>
</tr>
<tr>
<td>RWH System 5m³ Tank - Reuse 1</td>
<td>0.8</td>
<td>0.48</td>
</tr>
<tr>
<td>RWH System 10m³ Tank - Reuse 1</td>
<td>0.8</td>
<td>0.52</td>
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<tr>
<td>RWH System 15m³ Tank - Reuse 1</td>
<td>0.9</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>Greywater Recycling (GWR) for Reduced Consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWR System - Reuse 3</td>
<td>67.0</td>
<td>0.21</td>
</tr>
<tr>
<td><strong>Wastewater Reclamation (WWR) for Reduced Consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWR System - Reuse 2</td>
<td>16.7</td>
<td>2.22</td>
</tr>
</tbody>
</table>

CONCLUSION
This paper has set to assess domestic water end-use consumption and identify the viability of different water conservation measures in terms of their applicability, water savings and financial benefits for residential multi-storey buildings in the Federal District, Brazil. Findings pin-point indoor water consumption hot-spots from shower heads, washing machines, toilet flushes and kitchen faucets, suggesting that significant water reductions could be achieved through simple adaptation of existing water fixtures fittings and appliances with efficient water technologies at a low cost and high financial return. Water reuse systems for non-potable outdoor water end-uses were found to be easily adaptable to existing buildings; on the other hand, water reuse systems for non-potable indoor end-uses contained limitations which might lead to high costs and inconvenience to residents in order to adapt existing buildings. Although water reuse systems were capable of promoting significant reductions on water consumption, overall, most of them proved to be economically unviable options due to their high costs, suggesting that governmental policies and subsidies over taxes and interest rates could be used as means of promoting incentives for the general public to invest in water reuse systems.

REFERENCES