How much drinking water can be saved by using rainwater harvesting on a large urban area? Application to Paris agglomeration

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ABSTRACT

This paper is based on a prospective scenario of development of rainwater harvesting (RWH) on a given large urban area (such as metropolitan area or region). In such a perspective, a new method is proposed to quantify the related potential of potable water savings (PPWS) indicator on this type of area by adapting the reference model usually used on the building level. The method is based on four setting-up principles: gathering (definition of buildings-types and municipalities-types), progressing (use of an intermediate level), increasing (choice of an upper estimation) and prioritizing (ranking the stakes of RWH). Its application to the Paris agglomeration shows that is possible to save up to 11% of the total current potable water through the use of RWH. It also shows that the residential sector offers the most important part because it holds two-thirds of the agglomeration PPWS.

Key words | Paris agglomeration, rainwater harvesting, urban area, water saving

INTRODUCTION

Rainwater harvesting (RWH) is rapidly growing in urban areas. Nowadays, in France about 15% of the inhabitants are equipped with a RWH system (Cleau 2009). This diffusion begins to be significant and can be explained by various factors such as the emergence of new legislation (French Government Order of August 21st, 2008 that is related to RWH), incentive mechanisms developed by public bodies in order to foster this practice, and the increasing ‘green’ sensitivities of the different stakeholders (citizens, companies, and associations) (de Bellaing et al. 2009). For that purpose, beyond the building level, nowadays the RWH is a challenge especially for the urban area (Belmeziti 2012).

This article studies the potential impact for the use of rainwater on drinking water consumption (potential of potable water savings (PPWS) indicator) in an urban area. Currently, to study this indicator, there are two methods. The first method (representative building method) divides the urban area into several parties. Each of those parties is represented by one building (representative building) (Ghisi et al. 2007; Coombes et al. 2002). The second one (global building method) regards the urban area as a single entity. It considers all rainwater of this entity as PPWS (Ghisi et al. 2006; Abdulla & Al-Shareef 2009).

However, an urban area may not be represented by a unique representative building, because its buildings have different uses of water in terms of nature of the use, public concerned and frequency of use (Herrmann & Uwe 1999). Moreover, most buildings use only a portion of the rainwater that falls on their roofs (Khostagir & Jayasuriya 2010). Therefore, these methods potentially breed significant errors in the estimation of the PPWS for a given urban area.

This paper intends to propose a new method to calculate the PPWS indicator related to RWH. Such a method must (i) be reliable in terms of results (the margin of error...
should not exceed more than 10%), (ii) be adaptive to available data and (iii) have reasonable time of computation.

REFERENCE METHOD TO ASSESS THE PPWS AT THE BUILDING

The building is considered as the most appropriate level for calculating PPWS. This one can be expressed by two main indicators. The first called ‘RCHP’ (rainwater capture and harvesting potential) based on the assumption that all rainwater falls on the building’s roof and can be used instead of drinking water. It is calculated by the following equation:

\[
RCHP = RA \times RC \times R/1.000
\]

(1)

where:

- RCHP: rainwater capture and harvesting Potential (m³/year);
- RA: roof area (m²);
- RC: runoff coefficient (non-dimensional);
- R: rainfall (mm/year).

However, expressing PPWS by RCHP is not appropriate, because RCHP does not take into account the storage capacity and the building’s water needs (Appan 1999; Chilton et al. 1999; Coombes et al. 1999; Vialle et al. 2010; Farreny et al. 2011).

The second indicator called ‘RUP’ (rainwater utilization potential) is based on the simulation of the behavior of the real RWH system. There are several models to assess this indicator (Jenkins 1978; Appan 1999; Fewkes 1999). The most widely used today is Jenkins’ model (Jenkins 1978, quoted by Fewkes 1999), whereby, for a specific request for water, the model allows the water saving efficiency \( E(\%) \) to be expressed as a function of the storage volume \( V(m^3) \) to be drawn (Figure 1). In fact, \( E \) represents the ratio between rainwater used and total water demand. This curve is usually used by the engineering offices as a tool to help the decision-maker to choose the size of storage and to know the average PPWS expected in the RWH system.

For this, the engineering offices determine an ‘optimal area’. It is considered as the most favorable area between the capacity of the tank and water efficiency supply (Figure 1). The decision-maker is able to select a point within this area (optimal point).

de Gouvello et al. (2010) developed a method of an automatic extraction of this ‘optimal area’ based on the establishment of a series of points \((Un)\) of the curve. The sequence is defined as follows:

\[ U_0 = (0, 0) \] is the point of origin.

![Figure 1](https://iwaponline.com/wst/article-pdf/70/11/1782/175017/1782.pdf)
$U_1 = \text{Max} (E), \text{Min} (V)$ is the first point of the curve $E (V)$ from where the value of $E$ does not increase.

$U (n + 2)$ is the point where the tangent in the curve is parallel to the right segment $[U_n, U(n + 1)]$.

The authors showed that, considering the characteristic shape of this type of curve, point $U_2$ and point $U_3$ provide good approximations of the lower and superior borders of the ‘optimal area’. The decision-maker decides upon a point ($U_{opt}$) within this ‘optimal area’.

Finally, the RUP indicator is calculated by the following equation:

$$\text{RUP} = E(U_{opt}) \times D$$

Principle no. 1 (gathering principle): determining ‘buildings-types’ and ‘municipalities-types’

The principle consists of reducing the number of buildings for which PPWS has to be calculated. For this, the buildings are gathered into some ‘buildings-types’. Each one contains a set of buildings specifically selected (buildings-types identification). If the urban area is very large (as for a metropolis containing a lot of municipalities), the principle also applies by gathering the municipalities into ‘municipalities-types’ (municipalities-types identification).

Principle no. 2 (progressing principle): using an intermediate level

In the case of a large urban area, the municipality level is considered as a first gathering (the second being the ‘municipalities-types’). In this level (municipality) a large amount of data are available (population number, buildings’ distribution, etc).

Principle no. 3 (increasing principle): choosing the upper estimation

The PPWS calculation on an urban area is based on the same model used as for the building. So, in this case the decision maker selects a point in the ‘optimal area’ (Figure 1) to express the RUP demand. The principle of ‘the upper bound estimation’ is adopted for each building-type. For that purpose, the point $U_3$ (superior borders of the ‘optimal area’) is selected to express the RUP of buildings-types. This principle ensures a maximum of the PPWS value.

Principle no. 4 (prioritizing principle): ranking the stakes of RWH

To lighten the model of RUP calculation in a buildings-type, the principle of ‘prioritizing’ is adopted for the buildings-types and the municipalities-types. It aims to distinguish two types of buildings-types: significant buildings-types whose RWH potentials are important, and marginal buildings-types whose RWH potentials are marginal.

From a practical point of view, all buildings-types of an urban area whose cumulated RCHPs reaches 90% of the global RCHP of the urban area are considered as significant buildings-types.

Consequently, the rest of the buildings-types (whose RCHPs represent less than 10% of the global RCHP) are considered as marginal ones. For the significant buildings-types a detailed analysis has been conducted (data research, model calibration, etc.) to calculate the RUP indicator, while the corresponding contribution of the marginal buildings-types was calculated by the RCHP indicator. This principle is also applied for the municipalities-types.
Practical approach of ‘PPWS calculation’

Buildings-types identification

The RUP of buildings-type can be calculated as a single building, because it is equal or close to the result when considering the calculation of each building individually. It has been shown that the difference between the results of the two methods doesn’t exceed 10% (Belmeziti et al. 2013).

Such a result is only if the buildings of the building-type have the same ‘use scenario’ of RWH. Thus, use scenario is determined by three features: use (e.g. toilet flushing), ratio (e.g. 3 litres/m²) and frequency (e.g. once a week).

For creating a building-type, a database called ‘MOS’ (Modes d’Occupation des Sols – Modes of Land Use) developed by the Urban Planning and Development Institute for the Greater Paris region (IAU-IDF: Institut d’Aménagement et d’Urbanisme d’Ile-de-France) has been used. These data, which have been created to follow an urban development, offer a first gathering of buildings (MOS buildings).

To identify the buildings-types, the MOS buildings are confronted with gathering RWH criteria (use scenario). Two cases are possible:

- When two or more MOS buildings have the same use scenario, they merge into the same building-type.
- When a MOS building has two or more use scenarios, the division of this MOS into several buildings-types becomes necessary.

Municipalities-types identification

If there are many municipalities (a large urban area), the calculation method of PPWS for each municipality can be complex. In this case, it is possible to gather the municipalities into some municipalities-types. A municipality-type gathers municipalities with the same RWH profile. This profile is defined by the significant buildings-types. It puts in the same municipalities-types all municipalities dotted with the same significant buildings-types. Indeed, these municipalities have the same mode of RUP calculation, because this indicator is calculating just for significant buildings-types. The marginal buildings-types have no effect in this work because only their RCHPs are considered. For this, five stages are necessary:

Stage 1: describing each municipality by its buildings-types (buildings-types identification).  
Stage 2: calculating the RCHP for each building-type (Equation (1)).

Stage 3: linking the priorities of the buildings-types (Principle no. 4 ‘priorities’).  
Stage 4: The municipalities that have the same significant buildings-types will be gathered into the same municipality-type.  
Stage 5: linking the priorities of the municipalities-types (Principle no. 4 ‘priorities’).

PPWS calculation

For each significant municipality-type, the calculation of RUP is required for their significant buildings-types. Its PPWS is calculated as the following:

\[
PPWS_{\text{significant municipality-type}} = \sum \text{RUPs}_{\text{significant buildings-types}} + \sum \text{RCHPs}_{\text{marginal buildings-types}}
\]

To conclude, the PPWS of the large urban area is calculated as:

\[
PPWS_{\text{large urban area}} = \sum \text{RUPs}_{\text{significant municipalities-types}} + \sum \text{RCHPs}_{\text{significant municipalities-types}}
\]

CASE STUDY: PARIS AGGLOMERATION

In this section, the methodology described above is applied on the agglomeration of Paris. It contains 415 urban municipalities.

Modeling and calculation of the PPWS indicator

Preliminary stages

The role of these stages is to prepare the database for the calculation models:

- Creation of the buildings-types. In the MOS database, the urban space of each municipality is divided into 81 MOS, which are converted to buildings-types (each municipality contains 13 buildings-types as a maximum).
- Calculation of the RCHP of buildings-types. The variable ‘roof surface’ is directly inferred from the MOS database; it can be deduced for each building-type. The ‘rainfall’ is calculated by the annual average of 30 years of daily rainfall.

Stage 1: describing each municipality by its buildings-types (buildings-types identification).  
Stage 2: calculating the RCHP for each building-type (Equation (1)).

Stage 3: linking the priorities of the buildings-types (Principle no. 4 ‘priorities’).  
Stage 4: The municipalities that have the same significant buildings-types will be gathered into the same municipality-type.  
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PPWS_{\text{large urban area}} = \sum \text{RUPs}_{\text{significant municipalities-types}} + \sum \text{RCHPs}_{\text{significant municipalities-types}}
\]
rainfall data of Paris Montsouris meteorological station, and the runoff coefficient is fixed at 0.85 (average of buildings’ roofs).

- **Definition for municipalities-types.** Twenty-nine municipalities-types for the Paris agglomeration are identified based on the significant buildings-types of the 415 municipalities.
- **Relativizing the municipalities-types.** The Paris agglomeration has seven significant municipalities-types (the sum of their RCHP is greater than 90% compared to a global RCHP of Paris agglomeration) and 22 municipalities-types are considered as marginal (Table 1).

### Calculating the PPWS of significant municipality-type

The RUP for each significant building-type is first calculated. For this, three RUPs (Equation (2)) which correspond to three use scenarios of RWH are tested:

- **Uses scenario 1:** toilet flushing + watering + floor washing + washing machine (rainwater is used indoors outdoor).
- **Uses scenario 2:** toilet flushing + washing machine (rainwater is used only indoor).
- **Uses scenario 3:** watering + floor washing (rainwater is used only outdoor).

After that, the major value is chosen to represent the RUP of the building-type in question. The PPWS of significant municipality-type is calculated by using Equation (3) (Table 2 gives an example).

### PPWS of Paris agglomeration

The PPWS of the Paris agglomeration is calculated by using Equation (4) (Table 3).

### Analysis and interpretation of the results

The PPWS of the Paris agglomeration is compared with other indicators:

- **With RCHP indicator:** the PPWS of the Paris agglomeration is more than 81 million m³/year, which represents 64% of RCHP (more than 127 million m³/year). So, about

### Table 1 | The significant municipalities-types of Paris agglomeration

<table>
<thead>
<tr>
<th>Significant municipalities-types (SMT)</th>
<th>Number of the municipalities in each SMT</th>
<th>RCHP (m³/year)</th>
<th>Proportion to Paris agglomeration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant municipality-type no. 1</td>
<td>202</td>
<td>68.1 x 10⁶</td>
<td>53.59</td>
</tr>
<tr>
<td>Significant municipality-type no. 2</td>
<td>109</td>
<td>14.8 x 10⁶</td>
<td>11.67</td>
</tr>
<tr>
<td>Significant municipality-type no. 3</td>
<td>17</td>
<td>13.4 x 10⁶</td>
<td>10.56</td>
</tr>
<tr>
<td>Significant municipality-type no. 4</td>
<td>9</td>
<td>7.5 x 10⁶</td>
<td>5.78</td>
</tr>
<tr>
<td>Significant municipality-type no. 5</td>
<td>18</td>
<td>5.9 x 10⁶</td>
<td>4.68</td>
</tr>
<tr>
<td>Significant municipality-type no. 6</td>
<td>9</td>
<td>4.2 x 10⁶</td>
<td>3.33</td>
</tr>
<tr>
<td>Significant municipality-type no. 7</td>
<td>7</td>
<td>2.0 x 10⁶</td>
<td>1.58</td>
</tr>
<tr>
<td>Total</td>
<td>371</td>
<td>11.5 x 10⁷</td>
<td>91.19</td>
</tr>
</tbody>
</table>

### Table 2 | PPWS calculation of the significant municipality-type no. 1 of Paris agglomeration

<table>
<thead>
<tr>
<th>Significant municipality-type no. 1 of Paris agglomeration</th>
<th>RUP (m³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual housing</td>
<td>18.6 x 10⁶</td>
</tr>
<tr>
<td>Collective housing</td>
<td>13.8 x 10⁶</td>
</tr>
<tr>
<td>Secondary activities</td>
<td>1.6 x 10⁶</td>
</tr>
<tr>
<td>Primary schools</td>
<td>9.4 x 10⁵</td>
</tr>
<tr>
<td>Other marginal building-types</td>
<td>5.8 x 10⁶</td>
</tr>
<tr>
<td>PPWS</td>
<td>30.7 x 10⁶</td>
</tr>
</tbody>
</table>

### Table 3 | PPWS calculation of Paris agglomeration

<table>
<thead>
<tr>
<th>Municipalities-types of Paris agglomeration</th>
<th>PPWS (m³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant municipalities-types</td>
<td></td>
</tr>
<tr>
<td>Significant municipality-type no. 1</td>
<td>30.7 x 10⁶</td>
</tr>
<tr>
<td>Significant municipality-type no. 2</td>
<td>9.9 x 10⁶</td>
</tr>
<tr>
<td>Significant municipality-type no. 3</td>
<td>12.0 x 10⁶</td>
</tr>
<tr>
<td>Significant municipality-type no. 4</td>
<td>7.0 x 10⁶</td>
</tr>
<tr>
<td>Significant municipality-type no. 5</td>
<td>4.9 x 10⁶</td>
</tr>
<tr>
<td>Significant municipality-type no. 6</td>
<td>3.9 x 10⁶</td>
</tr>
<tr>
<td>Significant municipality-type no. 7</td>
<td>2.4 x 10⁶</td>
</tr>
<tr>
<td>Marginal municipality-types</td>
<td>10.2 x 10⁶</td>
</tr>
<tr>
<td>PPWS of Paris agglomeration</td>
<td>81.5 x 10⁶</td>
</tr>
</tbody>
</table>
36% (more than 45 million m³/year) of the rainwater is lost in the sewage system. This result confirms our starting assumption: the buildings use just a part of harvested rainfall that falls on their roofs.

With water volume consumed: More than 738 million m³ of drinking water are distributed annually throughout the Paris agglomeration. Thanks to PPWS, 11% of drinking water consumed in this area can be served. The important gap between ‘PPWS’ and ‘water volume consumed’ must be noted. This study shows that the current RWH practice (defined as collecting and harvesting rainwater from buildings’ roofs) can replace only a small part of drinking water. This must be combined with other practices to save more water.

Comparison between the involvement of different buildings-types: The residential sector (individual and collective housing) is the most important sector for RWH because it contributes 65% of the PPWS of the Paris agglomeration (Figure 2). This shows that the residential sector deserves special attention for any policy aimed at wide dissemination of RWH.

CONCLUSION

In this paper a new method to evaluate the PPWS indicator for any urban area is proposed. This method is based on the adaptation of the method usually used for the building level. For this adaptation, a double gathering process is conducted: buildings-types and municipalities-types.

The application of the method to the Paris agglomeration allows the calculation to be reduced stage and solves the problem of lack of some data. It also shows that the choice of scenario use of rainwater is to optimize the use of this resource.

The calculation of the PPWS to the Paris agglomeration shows that it possible to use two-thirds of the rainwater that falls on the buildings’ roofs. So, also notes that in the current context (regulation, urban, etc.) RWH is able to replace about a tenth of drinking water consumed across the Paris agglomeration. To increase this ratio, a regulatory change is necessary by allowing, firstly, other rainwater uses, and, secondly, rainwater recovery from other areas such as surface parking lots or different impervious surfaces of the city. In this case, further studies are needed on the quality of water and its possible uses.

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