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Abstract

The collection, storage and use of rainwater from roofs reduce the need for potable water. However if water suppliers are to decrease their infrastructure costs as well as their operational costs (due to water savings), the rainwater system has to provide most of the time a significant percentage of the water demand. This paper adopts the view point of the water suppliers and investigates how reliable this source of water is in the case of a housing estate, considering WC flushing as the only water demand. A housing estate was modelled and different realistic input scenarios (water demand for WC flushing, storage capacity, roof area, and rainfall) were defined. Three indicators were exhibited. The variability generated by each input on the indicators was evaluated. The indicators were estimated for 63 homogeneously distributed French cities. Among the indicators exhibited in this paper, the most relevant one is the percentage of water supplied from the tank that is secured during 95% of the days of the simulation. The main conclusion is that the optimum way of determining the storage capacity of the rainwater collection system is not the same from the viewpoint of the users than from

the viewpoint of the water suppliers. Indeed, water suppliers tend to require bigger tanks in order to take into account the rainwater collection systems in their management plan.

Key words: Rainwater collection, Modelling, Simulation, Water conservation, water utility management

1. Introduction

In the debate on sustainable water management, a growing place is given to rainwater. Rainwater tends to be considered more and more as a potential source to supply water to not only small isolated areas, but also existing towns or new urban projects. In many developing and developed countries such as Brazil (Ghisi, 2005; 2006), West Africa (Cowaken, 2008), Australia (Coombes, 1999) or Germany (Hermann, 1999; Nolde, 2007), rainwater harvesting and use within the building is already a widespread practice.

In France, despite a very restrictive regulatory framework limiting the use of rainwater to outdoor activities, this practice also started to grow from 2000 (de Gouvello et al., 2005). In 2008, a new specific regulation framework was sketched, authorising the use of rainwater *within* the building for several non potable uses: WC, floor cleaning and - under conditions still to be defined - washing machines. This new framework will foster the development of this practice and may have consequences on the water utilities' supply management. Several tools were developed to quantify these consequences. For instances Aquacycle (Mitchell, 2001), which is based on the concept of water balance of the urban water cycle permits to estimate the feasibility of alternative water management options and evaluate the performance of a re-use scheme, at different scales (Unit block, cluster, or catchment). An enhanced version, called Urban Volume and Quantity (Mitchell, 2003), that includes new flow paths and a contaminant balance model, was developed. The Probabilistic Urban Rainwater and wastewater Reuse Simulator (PURRS) by Coombes and Kuczera (2001) operates at 6 minute time steps to simulate and evaluate the efficiency of a reuse scheme.

Nevertheless, these models only highlight the overall performance of water management options. This paper suggests adopting the viewpoint of the water supplier and introduces new indicators evaluating the daily reliability of rainwater as a source of water. These indicators are relevant at a regional scale, that is to say a scale that includes the water treatment plant, the distribution network and the consumer. The sensitivity of these new indicators to each input was analysed. They were tested for 63 French cities in order to exhibit disparities. This paper focuses on the specific case of housing estates, as it seems to be a trouble-free area to equip with rainwater collection systems, since there is room to install the tanks and the roof area available per person is much greater than in denser parts of the city.

2. Model description and data

The aim of this paper is to analyse the behaviour of a housing estate in which all plots are equipped with rainwater collecting systems. In this paper, only the effects of individual systems are considered and collective systems (such as shared rainwater tanks) are not modelled. This housing estate model is more than a plot model multiplied by the number of plots since the features –and consequently the behaviour- of each plot will be different to better represent the real situation. Since this paper studies rainwater collection systems from the point of view of the water suppliers, we analyse the behaviour and define indicators for the whole housing estate and not only the behaviour of each plot.

2.1. Behaviour model of the rainwater collection system

In essence, a rainwater collection system works as described in Fig 1. The rainwater harvested by the catchment area (here the roof of the house) goes into a tank where it is stored until it is withdrawn to meet the water demand. If the volume exceeds the storage capacity, the runoff is overflowed elsewhere (sewage system, retention device...) and lost for usage. If the tank does not supply enough water to meet the demand, then the water is withdrawn from the water supply distribution network.

Jenkins et al. (1978) identified two algorithms to describe the behaviour of the collecting system during a given time interval. The yield after spillage (YAS) algorithm, in which the withdrawal occurs before the rainfall, is

$$Y_n = \min\begin{Bmatrix} D_n \\ V_{n-1} \end{Bmatrix} \quad (1)$$

$$V_n = \min\begin{Bmatrix} V_{n-1} + R_n - Y_n \\ S - Y_n \end{Bmatrix} \quad (2)$$

where R_n is the volume of rainwater captured (m^3) during time interval n (which is equal to the rainfall (m) during the time interval n multiplied by the roof area (m^2), neglecting any potential initial losses), V_n is the water volume in the tank (m^3) during time interval n, Y_n is the yield (m^3) during time interval n, D_n is the demand during time interval n, and S is the storage capacity (m^3).

The yield before spillage (YBS), in which the withdrawal occurs after the rainfall is

$$Y_n = \min\begin{Bmatrix} D_n \\ V_{n-1} + R_n \end{Bmatrix} \quad (3)$$

$$V_n = \min\begin{Bmatrix} V_{n-1} + R_n - Y_n \\ S \end{Bmatrix} \quad (4)$$

The YAS algorithm under evaluates the amount of water provided by the rainwater collection system, whereas YBS algorithm over evaluates it since there is less water in the tank to match the demand. In this investigation, each simulation was tested with both algorithms and the values obtained for the indicators were always similar. Therefore in this paper, the given value of an indicator corresponds to the mean of the values obtained from the simulations made with the YAS and the YBS algorithms.

Fewkes and Butler (2000) recommend using a daily model for a *storage fraction* (eg. the storage capacity of the tank divided by the rainwater captured in a year) belonging to the range 0.01-0.125[1]. Since the average storage fraction of the simulations carried out in this paper is 0.026, a daily model lasting five years has been used. It has to be mentioned that Coombes (2007a) showed that the use of 6 minute time steps lead to a better efficiency of the collecting systems. This effect is likely to be at least partly compensated by the use of the mean results of the YAS and YBS algorithms.

The YAS and YBS algorithms were both coded on Scilab[2] so that simulations could be performed.

2.2. <u>Realistic modelling of a housing estate</u>

To complete the housing estate model, realistic values for the water demand, the roof area, and the storage capacity were determined for each plot. In order to evaluate the variability created by each input, several scenarios were made.

[1] A smaller storage fraction would imply the use of an hourly time interval, and a bigger one would authorize the use of a monthly model.
[2] A free scientific software package developed under the responsibility of a consortium that includes INRIA, the French national institute for computer science.

The only water demand considered in this paper is WC flushing. In this simulation, the variability of the demand through the week was taken into account and not just the average demand. The average demand was determined from the C.I.Eau (Water information centre, a French association of the main water suppliers, which collects and publishes data on water). Data, which shows that WC flushing accounts for approximately 20% of the total domestic water demand of 137 litres per person per day. The average demand for WC flushing is therefore 27.4 l/person/day. Using the distribution data implemented by the experiment MARIA lead by the CSTB (de Gouvello et al., 2005), it has been possible to distribute the demand according to the day of the week. The demand considered per person per day is 24 l during the week, 37.7 l on Saturday, and 34.2 1 on Sunday. In the following sections of the paper, various scenarios were made, considering a range of 1 to 6 occupants per plot. A realistic distribution of people according to the plot was required. The INSEE (the French national institute of statistics) data from the 1999 census of the French population was used. The figures are only available for cities, so it was necessary to select cities that have a homogenous pattern (mainly housing estate areas and very few buildings). City patterns were checked using satellite images. Since the distribution of inhabitants of the cities having the correct features did not exhibit (for the thirteen selected cities) clear regional tendency, i.e. the regional differences are comparable to the differences between cities in the suburb of the same larger one, it was decided to select only two cities, of which the inhabitants distributions are displayed in Tab 1. These two cities were chosen because they represent two different kinds of inhabitants' distribution: Vendeville (North of France, in the suburb of Lille) is a city where there are mainly families (more than half of the houses are occupied by three or more people) whereas Génémos (South of France, in the suburb of Marseilles) is a city where there are mainly single persons or couples (more than half of the houses are occupied by one or two people). In this paper we refer to Vendeville as the family option, and Génémos as the couple option.

Since this paper adopts the viewpoint of the water supplier, that is to say what it definitely expects, the storage capacities are not optimised according to the region as it was done in previous studies (Coombes; 2007b; Aquacycle users guide; 2005). Several realistic scenarios were built for the sizes of the tanks using the following methodology, which is based on the householders' needs. In the experiment of MARIA lead by the CSTB in Champs-sur-Marne (about 25 km from Paris), de Gouvello et al. (2005) showed that a storage capacity that corresponds to approximately 4 weeks of the water demand is almost always enough to ensure the autonomy of the installation. It has been shown that this ratio is only an optimum for customers in the region of Paris. Nevertheless it is adopted for all French cities, knowing that it might not always be optimum for the customer. Yet the results obtained here show that this ratio works all over France. In the following sections of the paper, several scenarios were made knowing that people will not necessarily choose the optimum storage capacity (saving money, change of owner, birth, departure of a child...). Since the number of people per plot ranges from 1 to 6, the storage capacity chosen in this paper ranges from 0.5 to 4 m^3.[3] As the daily rainfall time series used in the simulations last for a duration of 5 years, it is not necessary to have different starting configurations for the tank. Indeed they will all be notably full after the first major rainfall or notably empty after the first drought period.

The only catchment area considered in this paper is the roof. An average projected roof area of 100-120 m^2 was estimated by observing Google Earth images of the selected cities used to model the distribution of people according to the plot. The roof area chosen in the scenarios of the following sections ranges from 60 to 160 m^2.

[3] The considered storage capacity in this paper are 0.5 ; 0.75 ; 1.3 ; 2 ; 3 and 4 m^3

The daily rainfall time series are supplied by Meteo-France for a duration of five years (1994-1998). Series for 63 French cities were used. A time series lasting 30 years (1976-2005) for Paris was also available and tested. The distribution of cities in France is quite homogenous, so it can be considered that they are representative of the climates in France over a period of five years.

3. Towards the definition of relevant indicators

The usual indicator (Fewkes, 2000) used to evaluate the performance of a rainwater collecting system is the water-saving efficiency (E). It is equal to the percentage of the overall demand of the WC flushing supplied by the tank during N time intervals. It is given by the following equation:

$$E = \frac{\sum_{n=1}^{N} Y_n}{\sum_{n=1}^{N} D_n} * 100 \quad (5)$$

This indicator is interesting for the consumer since it determines whether the collection system is efficient and beneficial. It also permits to estimate the possible savings in energy (pumping, treatments …) that the water supplier can expect in operational costs (Coombes, 2007). However it does not give any information on the regional impact of a generalised rainwater collection on the infrastructure costs (size of the pipes, the pumps, the water treatment works, …). To be able to decrease the latter costs, water suppliers need to evaluate the reliability of this source of water. If ever the systems do not supply enough water to meet the demand, the supplier will be expected to do so and therefore should not reduce the size of its infrastructure. To estimate this reliability, the authors suggest using a “reliability curve”, which is drawn for each simulation. Refer to Fig 2 for an example. To read this curve, a percentage of water volume supplied by the tank is chosen on the vertical axis, and the corresponding value on the horizontal axis gives the proportion of days when this percentage is reached.

From this curve, three reliability indicators (RI) are estimated:

- RI1: the percentage of days the tank supplies 100% of the demand for WC flushing. This indicator was also analysed for 95% and 90%. The value 100% was chosen because it generated the indicator with the highest sensitivity among the French cities, making it the most relevant. This indicator corresponds to the "event reliability" used in Aquacycle (Users guide, 2005). On the curve in Fig 2, RI1 is equal to 58%.

- RI2: the percentage of days the tank supplies less than 10% of the water demand. It was also studied with 5% and 0%, but the sensitivity among the French cities was greater for the value of 10%. On the curve in Fig 2, RI2 is equal to 3%.

- RI3: the percentage of water supplied by the tank over 95% of the days of the simulation. To estimate this, the daily water-saving efficiency (Y_n / D_n) is evaluated for all the days of the series. RI3 is the lowest daily water-saving efficiency. This indicator was also analysed for 90% and 100%. The value 95% was chosen because it generated the indicator with the highest sensitivity amongst the French cities, making it the most relevant. On the curve in Fig 2, RI3 is equal to 24%.

Even though all the indicators are percentages, it is important to note that the first two are percentages of days, whereas the third is a percentage of water demand supplied. If RI1 is too small or RI2 too great, it implies that the water supplier will not be able to decrease their infrastructure costs because rainwater is not a reliable enough source of water. RI3 gives an idea of the possible reliable demand reduction. For example if RI3 is equal to 20 % then the water supplier can expect a reduction in the water demand of 4% (the WC flushing usage represents 20% of the potable household water usage in France) with very limited risks for its customers.

4. Results and discussion

In the first part of this section the sensitivity of the indicators for each input is evaluated. This is done by analysing the variability generated on the indicators when the input scenarios change. This allows defining relevant scenarios to estimate the indicators for 63 French cities. An analysis of the values of the indicator in France was then performed.

4.1. Analysing the sensitivity

4.1.1. Methodology of investigation

In order to evaluate the variability generated by each input, seven options were tested for each input on a housing estate consisting of ten plots. Since a scenario is defined from different combinations of the inputs, a total of 2401 (=7*7*7*7) scenarios were tested. The options, based on the values found in the first section, are presented in Fig 3. Since the aim is to estimate the variability, some of the chosen options may not look very realistic. Concerning the chosen rain sites, they are homogeneously distributed over the French territory, which permits to have a set of different French climates. Then the four indicators were estimated via a computer coded simulation for each set of options. The results were put in arrays E, RI1, RI2, and RI3, whose sizes are 7*7*7*7. In the following, the chosen rain option is represented by the index i, the inhabitant option by j, the roof area option by k, and the store capacity option by l.

The same method was used to analyse the variability of each indicator, and is described here for the indicator RI1. It consists in keeping three inputs constant while the fourth changes. For instance, the rain_standard_deviation array (whose size is 7*7*7) was evaluated to analyse the input "rain". The term (j,k,l) of this array is the standard deviation of the set $\{RI1(i, j, k, l), i \in \{1,2,..7\}\}$. Then the average variability generated by the rain on the RI1 indicator is the mean of this array. In order to evaluate the reliability of this average variability, the standard deviation of the array was also evaluated. If it is too great compared to the average variability, it means that this average variability is not very reliable.

The same procedure was then followed for each input.

4.1.2. Variability created by each input

The results for the variability generated by each input are shown in Tab 2.

First of all, it can be noted that the variability generated by the rain is the most important, which is one of the reasons why a geographical analysis was performed and is explained in the next section. The duration (5 years) of the rainfall time series did not permit to perform a temporal analysis of the evolution of these indicators for a given city. The variability created by the various distributions of inhabitants is quite important. However the chosen options were quite extreme and the actual repartition is more homogenous so in reality, this input will not create much variability. The roof area is the input that generates the less variability. This is due to the fact, that when it rains, it often rains more than necessary to fill the tank, so that even a small roof fills the rainwater collection system. The variability generated by the storage capacity is important, which confirms (Lucas, 2006) that people should be very careful when they are choosing the optimum size of their tank. The disparities existing among the different scenarios are highest for RI3. This will be confirmed in the next section as a geographical analysis shows great disparities among the cities, making RI3 a very relevant indicator to distinguish between the sites.

These values of average variability must be considered very carefully because their reliability is not very good. This is due to the fact that there are many disparities between the chosen options to perform the investigation. Since the averaged variability is often quite high, a more precise analysis is required to decide whether the water supplier can take the existence of rainwater collection systems into account in their management plan. This is explained in the next section.

4.2. Results for 63 French Cities

As explained in the previous section it is not possible to give a unique answer to whether water suppliers can take into account a water demand reduction in their management plan if there is a generalised installation of rainwater collection system.

In this section a geographical analysis was performed. Several realistic options were defined for each input on a housing estate consisting of 100 plots, so that the estimated figures are reliable. These options are presented in Fig 4. Since the variability generated by the inhabitants is not substantial, only two options were considered for the number of occupants, whereas three were considered for the storage capacity. Only one was considered for the roof area since this input does not generate much variability. As a geographical analysis is performed the only rain option considered is the daily rainfall time series of the considered city. This means that for each city 6 (=2*1*3*1) scenarios were considered. The average RI1, RI2, and RI3 were figured for 63 French cities.

For each indicator the mean, the standard deviation, the minimum and the maximum are presented in Tab 3. First of all, the average E is 93.5%, with a small standard deviation of 5.3%, confirming that the storage capacity determined all over France with the help of an optimum in the region of Paris, is correct. However we can note that it might be slightly undersized for some cities since the minimum is 75.1%. As it can be seen RI1 ranges from 45.6% to 86.5%, which means that this indicator is relevant to exhibit disparities and that the water suppliers can consider it will not be smaller than 40%. The map of this indicator is presented in Fig 5. RI2 ranges from 0.1 to 10.2 according to the city. This shows that even if this indicator remains interesting for the water supplier, since it can be considered to always be a low value, there are no big disparities among the French cities, so a map of this indicator was not included in this paper. Concerning RI3, the value ranges from 6.2 to 93.8 which makes this indicator a very relevant way to compare the cities according to the reliability of the water supplied by a collection system. This is why we are going to focus our analysis on this indicator. The map of this indicator in France is presented in Fig 5. Fig 6 presents RI3 for each city, sorted in order according to increasing values of RI3.

The 30 year long time series over Paris was split into 6 series of 5 years each. All indicators were assessed for each period, and the main statistics are displayed on table 4. The standard deviation generated by the temporal differences (tab 4) is much smaller than the one generated by the spatial differences of rain (tab 3). This means that figures 5 and 6 remain relevant despite using rainfall time series lasting only 5 years. Nevertheless further investigations would require the use of longer series to achieve more robust results.

It is worth noting that the pattern shown in Fig 6 may be representative of the French territory. An analysis with more cities would permit to confirm this. With the help of Fig 6, it is possible to define three clusters of cities: not reliable (RI3 ranges from 0% to 50%), reliable (RI3 ranges from 50% to 70%)), and highly reliable (RI3 ranges from 70% to 100%). These clusters permit to define 5 areas in France (shown in Fig 5), which appear to be stratified according to a direction South-West, North-East:

- 1 and 3 : these areas are highly reliable
- 2: the disparities among cities that are close together do not permit to exhibit a clear tendency. Rainfall series from more cities would be required to make a deeper analysis.
- 4: this area is reliable. It is between a highly reliable area and an unreliable area, which means that the evolution of the indicators whilst moving from South-East to North-West appears to be continuous.
- 5: this area corresponding to the Mediterranean coast is absolutely unreliable. It is important to note that this is the only large area clearly not reliable in France.

E is almost always a high value and does not exhibit a lot of disparities in France, whereas RI3 varies in a wide range of figures. This means that the optimum way of determining the storage capacity of the rainwater collection system is not the same if you adopt the viewpoint of the customers or if you adopt the water suppliers'. Indeed the water suppliers tend to require bigger tanks to be able to take into account the rainwater collection systems in their management plans. Therefore water suppliers should advocate the use of indicators such as RI1, RI2 or RI3 and not only E for optimising the tanks' sizes so that they can diminish not only their operational costs but also their infrastructure costs. Nevertheless, listing and quantifying the savings are beyond the scope of this article and would require further investigation.

5. Conclusion

In this paper, the reliability of the water provided by rainwater collection systems is investigated for a housing estate. Indeed, if water suppliers are to take into account collection systems as a source of water in their management plan, it needs to have a certain level of reliability. The point of view of the water suppliers was adopted to define three indicators which have been assessed for 63 homogeneously distributed French cities.

The main conclusions are:

- The three interesting indicators for the water suppliers are: the percentage of days the tank supplies 100% of the demand for WC flushing, the percentage of days the tank supplies less than 10% of the water demand, and the percentage of water supplied by the tank secured 95% of the days of the simulation. The latter is the most relevant since it permits to exhibit the most disparities amongst the chosen cities.
- The optimum way of determining the storage capacity of the rainwater collection system is not the same if we adopt the point of view of the customers or if we adopt the water suppliers'. Indeed the water suppliers tend to require bigger tanks.
- Even if there are many disparities among the chosen French cities, it is possible to define five areas according to the reliability of the rainwater. It seems that France is stratified according to a direction South-West, North-East.

The only water demand taken into account in this paper is WC flushing. Studies involving other kinds of demands such as washing-machine demands are required. In this paper, the simulations are performed with daily rainfall time series of duration of five years. Using a longer duration and smaller time step for the series would allow analysing the evolution of the indicators at a given location. On top of this, the consequences of climate change could be investigated. Since water work systems are long term investments, this aspect of the issue should be studied very carefully. Further investigation should be performed to analyse the effect of sizing the tank from the viewpoint of the water suppliers. This would consists in applying standard techniques such as the "percentage rate of change of an indicator" (see Aquacycle users manual), not according to water saving efficiency as it is usually done, but to the reliability indicators.

Water suppliers are providing water to many kinds of urban areas. Therefore to fully assess the potential infrastructure costs reduction due to rainwater collection; it would be required to develop comparable models for urban areas other than housing estates. For instance investigation on heavily dense areas with high-rise buildings (here the roof areas are much smaller), or manufacturing district (high level of demand, and large potential roof areas) should be carried out.

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Figures

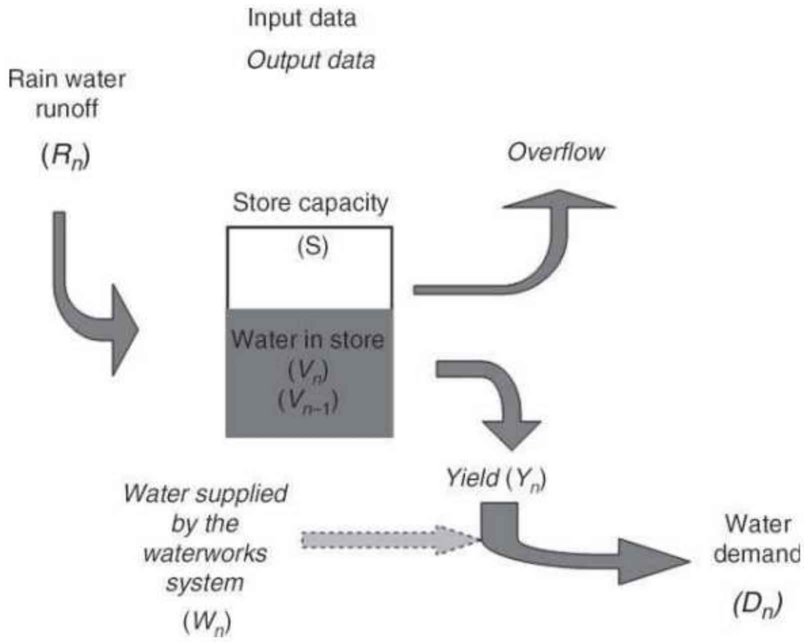

Fig 1: Description of a rainwater collection system

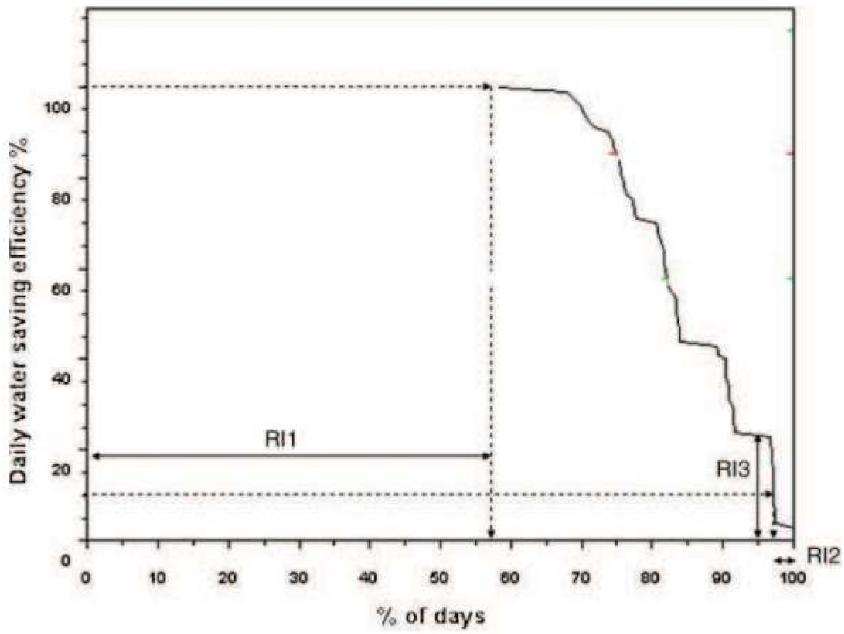

Fig 2: Example of a reliability curve for a simulation of a housing estate of 100 plots with the population distribution of the couples option, a roof area of 110 m^2 for all plots, a storage capacity of 1.3 m^3 for all plots, and a rainfall series from Saint-Nazaire (West of France).

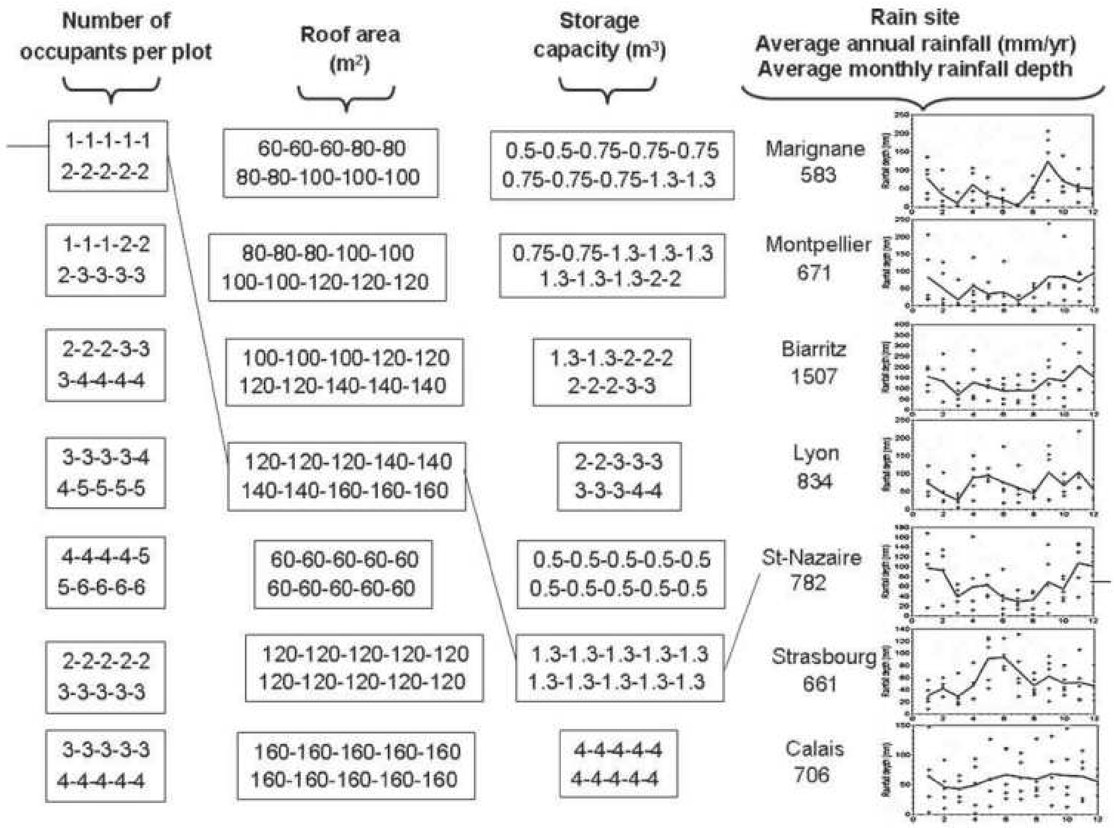

Fig 3: The chosen options to analyse the variability generated by each input. The modelled housing estate consists of 10 plots. For each input, 7 options were defined, in turn defining 7*7*7*7 scenarios. Defining a scenario consists in selecting one option for each input, as it can be seen in the example.

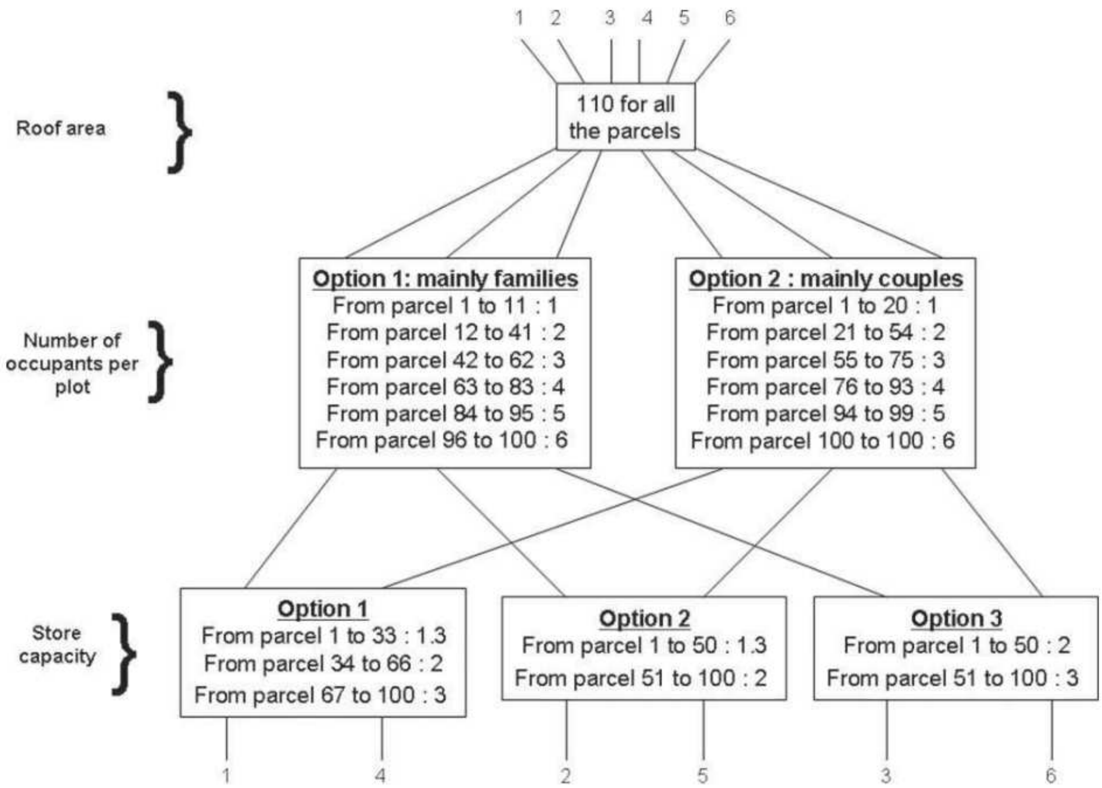

Fig 4: Definition of the chosen scenarios to perform the geographical analysis. The modelled housing estate consists of 100 plots. Three options were defined for the storage capacity, one for the roof area, and 2 for the number of people per plot. Therefore 6 scenarios (=3*1*2*1) were considered for each city. The dash represents a scenario.

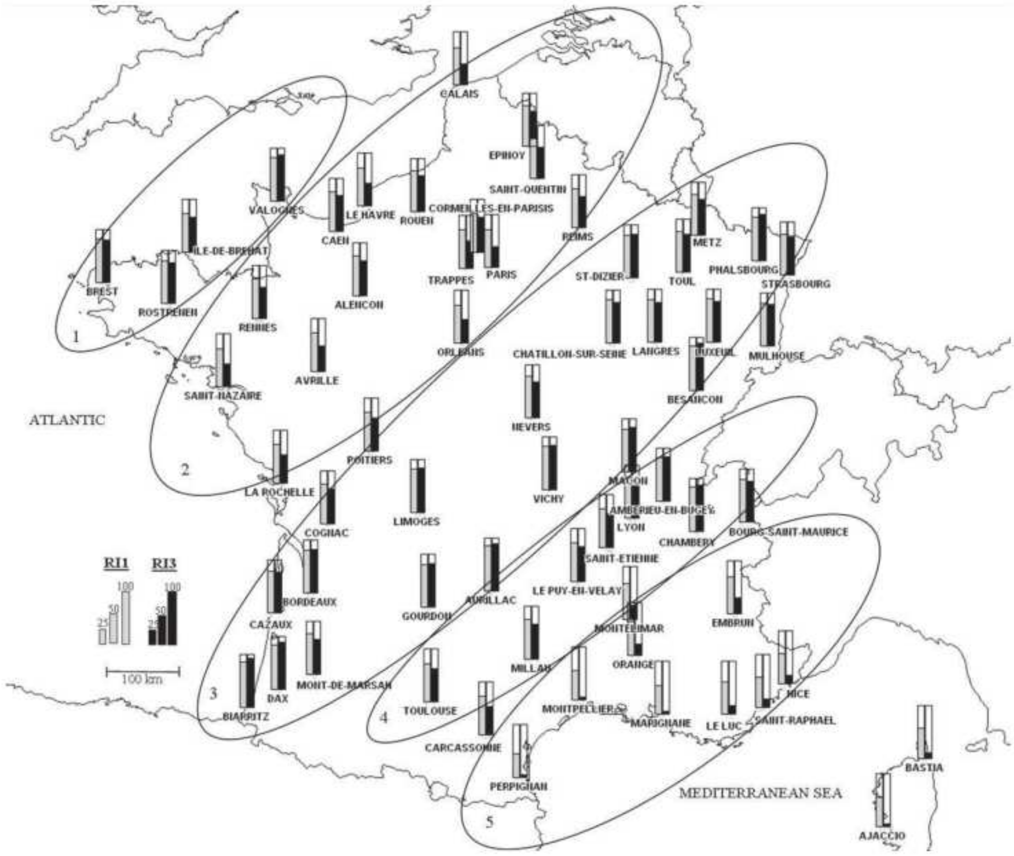

Fig 5: The RI1 indicator (the percentage of days the tank supplies 100% of the demand for WC flushing) and the RI3 indicator (the percentage of water supplied by the tank being secured for 95% of the days of the simulation) for 63 French cities. Five main areas are also represented.

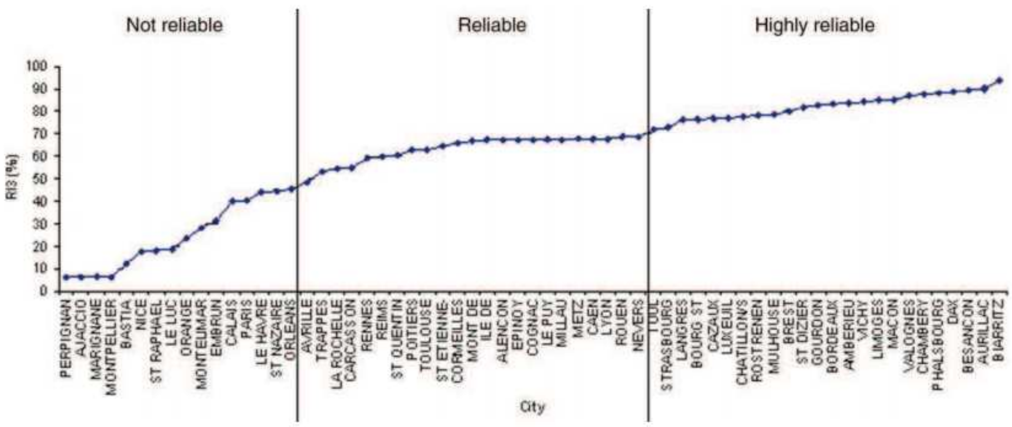

Fig 6: RI3 versus the cities (which have previously been sorted in order according to increasing value of RI3), and the definition of three clusters of cities

Tables:

Table 1 : Distribution of the occupants according to the plot of the two considered options for the repartition. The mainly families option corresponds to the city of Vendeville (North of France), whereas the mainly couples option corresponds to the city of Ge ´ ne ´mos (South of France). Both cities are looking like a housing estate. (The figures are coming from the 1999 INSEE census of the French population)

	Mainly families option	Mainly couples option
The houses		
Number of houses	479	2233
% of individual houses	91.2	87.7
The occupants		
% of house with 1 people	10.7	19.5
% of house with 2 people	29.6	34.3
% of house with 3 people	21.1	20.8
% of house with 4 people	20.8	17.6
% of house with 5 people	12.5	6.1
% of house with 6 people or more	5.3	1.4

Table 2 : Variability generated by each input on the different indicators

Input	E	RI1	RI2	RI3
Rain	30.8	28.0	32.4	24.9
Occupants	6.6	11.9	5.7	19.1

Roof area	2.6	3.2	1.6	5.6
Storage capacity	7.9	9.7	5.5	22.1

Table 3: The mean, the standard deviation, the minimum and maximum of each indicator, which have been evaluated for 63 French cities

	E	RI1	RI2	RI3
Mean	93.5	74.6	1.7	60
Standard deviation	5.3	8.7	2.4	24.6
Minimum	75.1	45.6	0.1	6.2
Maximum	98.6	86.5	10.2	93.8

Table 4: Statistics of the indicators, evaluated in the Paris area for 6 rainfall time series lasting 5 years between 1975 and 2006

	E	RI1	RI2	RI3
Mean	94.7	74.2	0.8	60.9
Standard deviation	1.3	2.3	0.6	10.7
Minimum	93.4	72.0	0.3	46.4
Maximum	96.4	78.0	1.6	71.2
1976–2005	94.8	74.4	0.7	66.8