



HAL
open science

Consequences to water suppliers of collecting rainwater on housing estates

Auguste Gires, Bernard de Gouvello

► **To cite this version:**

Auguste Gires, Bernard de Gouvello. Consequences to water suppliers of collecting rainwater on housing estates. *Water Science and Technology*, 2009, 60 (3), pp.543-553. hal-00816788

HAL Id: hal-00816788

<https://enpc.hal.science/hal-00816788>

Submitted on 8 Apr 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Consequences to water suppliers of collecting rainwater on housing estates

Auguste Gires (auguste.gires@cereve.enpc.fr) (1) ; Bernard de Gouvello (1,2)

(1) Université Paris-Est, Leesu, UMR MA 102 AgroParisTech, 6-8 avenue Blaise Pascal, F 77455 Marne la Vallée cedex 2

(2) Centre scientifique et technique du bâtiment, 84 av Jean Jaurès, F 77421 Marne la Vallée Cedex 2

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

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

27

28

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

31

32 **1. Introduction**

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

39 In France, despite a very restrictive regulatory framework limiting the use of rainwater to
40 outdoor activities, this practice also started to grow from 2000 (de Gouvello et al., 2005). In
41 2008, a new specific regulation framework was sketched, authorising the use of rainwater
42 *within* the building for several non potable uses: WC, floor cleaning and - under conditions
43 still to be defined - washing machines. This new framework will foster the development of
44 this practice and may have consequences on the water utilities' supply management. Several
45 tools were developed to quantify these consequences. For instances Aquacycle (Mitchell,
46 2001), which is based on the concept of water balance of the urban water cycle permits to
47 estimate the feasibility of alternative water management options and evaluate the performance
48 of a re-use scheme, at different scales (Unit block, cluster, or catchment). An enhanced
49 version, called Urban Volume and Quantity (Mitchell, 2003), that includes new flow paths

50 and a contaminant balance model, was developed. The Probabilistic Urban Rainwater and
51 wastewater Reuse Simulator (PURRS) by Coombes and Kuczera (2001) operates at 6 minute
52 time steps to simulate and evaluate the efficiency of a reuse scheme.
53 Nevertheless, these models only highlight the overall performance of water management
54 options. This paper suggests adopting the viewpoint of the water supplier and introduces new
55 indicators evaluating the daily reliability of rainwater as a source of water. These indicators
56 are relevant at a regional scale, that is to say a scale that includes the water treatment plant,
57 the distribution network and the consumer. The sensitivity of these new indicators to each
58 input was analysed. They were tested for 63 French cities in order to exhibit disparities. This
59 paper focuses on the specific case of housing estates, as it seems to be a trouble-free area to
60 equip with rainwater collection systems, since there is room to install the tanks and the roof
61 area available per person is much greater than in denser parts of the city.

62

63 **2. Model description and data**

64

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

73

74 **2.1. Behaviour model of the rainwater collection system**

75

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

82

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

86
$$Y_n = \min \left\{ \begin{array}{l} D_n \\ V_{n-1} \end{array} \right\} \quad (1)$$

87
$$V_n = \min \left\{ \begin{array}{l} V_{n-1} + R_n - Y_n \\ S - Y_n \end{array} \right\} \quad (2)$$

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

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

94
$$Y_n = \min \left\{ \begin{array}{l} D_n \\ V_{n-1} + R_n \end{array} \right\} \quad (3)$$

95
$$V_n = \min \left\{ \begin{array}{l} V_{n-1} + R_n - Y_n \\ S \end{array} \right\} \quad (4)$$

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

102 Fewkes and Butler (2000) recommend using a daily model for a *storage fraction* (eg.
103 the storage capacity of the tank divided by the rainwater captured in a year) belonging to the
104 range 0.01-0.125¹. Since the average storage fraction of the simulations carried out in this
105 paper is 0.026, a daily model lasting five years has been used. It has to be mentioned that
106 Coombes (2007a) showed that the use of 6 minute time steps lead to a better efficiency of the
107 collecting systems. This effect is likely to be at least partly compensated by the use of the
108 mean results of the YAS and YBS algorithms.

109 The YAS and YBS algorithms were both coded on Scilab² so that simulations could be
110 performed.

111

112 **2.2. Realistic modelling of a housing estate**

113

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

117

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.

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

142 people). In this paper we refer to Vendeville as the family option, and Génémos as the couple
143 option.

144

145 Since this paper adopts the viewpoint of the water supplier, that is to say what it
146 definitely expects, the storage capacities are not optimised according to the region as it was
147 done in previous studies (Coombes; 2007b; Aquacycle users guide; 2005). Several realistic
148 scenarios were built for the sizes of the tanks using the following methodology, which is
149 based on the householders' needs. In the experiment of MARIA lead by the CSTB in
150 Champs-sur-Marne (about 25 km from Paris), de Gouvello et al. (2005) showed that a storage
151 capacity that corresponds to approximately 4 weeks of the water demand is almost always
152 enough to ensure the autonomy of the installation. It has been shown that this ratio is only an
153 optimum for customers in the region of Paris. Nevertheless it is adopted for all French cities,
154 knowing that it might not always be optimum for the customer. Yet the results obtained here
155 show that this ratio works all over France. In the following sections of the paper, several
156 scenarios were made knowing that people will not necessarily choose the optimum storage
157 capacity (saving money, change of owner, birth, departure of a child...). Since the number of
158 people per plot ranges from 1 to 6, the storage capacity chosen in this paper ranges from 0.5
159 to 4 m³.³ As the daily rainfall time series used in the simulations last for a duration of 5 years,
160 it is not necessary to have different starting configurations for the tank. Indeed they will all be
161 notably full after the first major rainfall or notably empty after the first drought period.

162 The only catchment area considered in this paper is the roof. An average projected
163 roof area of 100-120 m² was estimated by observing Google Earth images of the selected
164 cities used to model the distribution of people according to the plot. The roof area chosen in
165 the scenarios of the following sections ranges from 60 to 160 m².

³ The considered storage capacity in this paper are 0.5 ; 0.75 ; 1.3 ; 2 ; 3 and 4 m³

166 The daily rainfall time series are supplied by Meteo-France for a duration of five years
167 (1994-1998). Series for 63 French cities were used. A time series lasting 30 years (1976-
168 2005) for Paris was also available and tested. The distribution of cities in France is quite
169 homogenous, so it can be considered that they are representative of the climates in France
170 over a period of five years.

171

172 **3. Towards the definition of relevant indicators**

173

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

$$178 \quad E = \frac{\sum_{n=1}^N Y_n}{\sum_{n=1}^N D_n} * 100 \quad (5)$$

179 This indicator is interesting for the consumer since it determines whether the
180 collection system is efficient and beneficial. It also permits to estimate the possible savings in
181 energy (pumping, treatments ...) that the water supplier can expect in operational costs
182 (Coombes, 2007). However it does not give any information on the regional impact of a
183 generalised rainwater collection on the infrastructure costs (size of the pipes, the pumps, the
184 water treatment works, ...). To be able to decrease the latter costs, water suppliers need to
185 evaluate the reliability of this source of water. If ever the systems do not supply enough water
186 to meet the demand, the supplier will be expected to do so and therefore should not reduce the
187 size of its infrastructure. To estimate this reliability, the authors suggest using a “reliability
188 curve”, which is drawn for each simulation. Refer to Fig 2 for an example. To read this curve,

189 a percentage of water volume supplied by the tank is chosen on the vertical axis, and the
190 corresponding value on the horizontal axis gives the proportion of days when this percentage
191 is reached.

192

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

194 - RI1: the percentage of days the tank supplies 100% of the demand for WC flushing.

195 This indicator was also analysed for 95% and 90%. The value 100% was chosen because it
196 generated the indicator with the highest sensitivity among the French cities, making it the
197 most relevant. This indicator corresponds to the “event reliability” used in Aquacycle (Users
198 guide, 2005). On the curve in Fig 2, RI1 is equal to 58%.

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

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

208 Even though all the indicators are percentages, it is important to note that the first two
209 are percentages of days, whereas the third is a percentage of water demand supplied. If RI1 is
210 too small or RI2 too great, it implies that the water supplier will not be able to decrease their
211 infrastructure costs because rainwater is not a reliable enough source of water. RI3 gives an
212 idea of the possible reliable demand reduction. For example if RI3 is equal to 20 % then the
213 water supplier can expect a reduction in the water demand of 4% (the WC flushing usage

214 represents 20% of the potable household water usage in France) with very limited risks for its
215 customers.

216

217 **4. Results and discussion**

218

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

223

224 **4.1. Analysing the sensitivity**

225

226 **4.1.1. Methodology of investigation**

227

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

239

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

248 The same procedure was then followed for each input.

249

250 4.1.2. Variability created by each input

251

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

253

254 First of all, it can be noted that the variability generated by the rain is the most
255 important, which is one of the reasons why a geographical analysis was performed and is
256 explained in the next section. The duration (5 years) of the rainfall time series did not permit
257 to perform a temporal analysis of the evolution of these indicators for a given city. The
258 variability created by the various distributions of inhabitants is quite important. However the
259 chosen options were quite extreme and the actual repartition is more homogenous so in
260 reality, this input will not create much variability. The roof area is the input that generates the
261 less variability. This is due to the fact, that when it rains, it often rains more than necessary to
262 fill the tank, so that even a small roof fills the rainwater collection system. The variability
263 generated by the storage capacity is important, which confirms (Lucas, 2006) that people

264 should be very careful when they are choosing the optimum size of their tank. The disparities
265 existing among the different scenarios are highest for RI3. This will be confirmed in the next
266 section as a geographical analysis shows great disparities among the cities, making RI3 a very
267 relevant indicator to distinguish between the sites.

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

274

275

276 **4.2. Results for 63 French Cities**

277

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

281 In this section a geographical analysis was performed. Several realistic options were
282 defined for each input on a housing estate consisting of 100 plots, so that the estimated figures
283 are reliable. These options are presented in Fig 4. Since the variability generated by the
284 inhabitants is not substantial, only two options were considered for the number of occupants,
285 whereas three were considered for the storage capacity. Only one was considered for the roof
286 area since this input does not generate much variability. As a geographical analysis is
287 performed the only rain option considered is the daily rainfall time series of the considered

288 city. This means that for each city 6 (=2*1*3*1) scenarios were considered. The average RI1,
289 RI2, and RI3 were figured for 63 French cities.

290

291 For each indicator the mean, the standard deviation, the minimum and the maximum
292 are presented in Tab 3. First of all, the average E is 93.5%, with a small standard deviation of
293 5.3%, confirming that the storage capacity determined all over France with the help of an
294 optimum in the region of Paris, is correct. However we can note that it might be slightly
295 undersized for some cities since the minimum is 75.1%. As it can be seen RI1 ranges from
296 45.6% to 86.5%, which means that this indicator is relevant to exhibit disparities and that the
297 water suppliers can consider it will not be smaller than 40%. The map of this indicator is
298 presented in Fig 5. RI2 ranges from 0.1 to 10.2 according to the city. This shows that even if
299 this indicator remains interesting for the water supplier, since it can be considered to always
300 be a low value, there are no big disparities among the French cities, so a map of this indicator
301 was not included in this paper. Concerning RI3, the value ranges from 6.2 to 93.8 which
302 makes this indicator a very relevant way to compare the cities according to the reliability of
303 the water supplied by a collection system. This is why we are going to focus our analysis on
304 this indicator. The map of this indicator in France is presented in Fig 5. Fig 6 presents RI3 for
305 each city, sorted in order according to increasing values of RI3.

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

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

- 318 - 1 and 3 : these areas are highly reliable
- 319 - 2: the disparities among cities that are close together do not permit to exhibit a
320 clear tendency. Rainfall series from more cities would be required to make a
321 deeper analysis.
- 322 - 4: this area is reliable. It is between a highly reliable area and an unreliable area,
323 which means that the evolution of the indicators whilst moving from South-East to
324 North-West appears to be continuous.
- 325 - 5: this area corresponding to the Mediterranean coast is absolutely unreliable. It is
326 important to note that this is the only large area clearly not reliable in France.

327

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

336 listing and quantifying the savings are beyond the scope of this article and would require
337 further investigation.

338

339 **5. Conclusion**

340

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

346 The main conclusions are:

347 - The three interesting indicators for the water suppliers are: the percentage of days the
348 tank supplies 100% of the demand for WC flushing, the percentage of days the tank supplies
349 less than 10% of the water demand, and the percentage of water supplied by the tank secured
350 95% of the days of the simulation. The latter is the most relevant since it permits to exhibit
351 the most disparities amongst the chosen cities.

352 - The optimum way of determining the storage capacity of the rainwater collection
353 system is not the same if we adopt the point of view of the customers or if we adopt the water
354 suppliers'. Indeed the water suppliers tend to require bigger tanks.

355 - Even if there are many disparities among the chosen French cities, it is possible to
356 define five areas according to the reliability of the rainwater. It seems that France is stratified
357 according to a direction South-West, North-East.

358

359 The only water demand taken into account in this paper is WC flushing. Studies
360 involving other kinds of demands such as washing-machine demands are required. In this

361 paper, the simulations are performed with daily rainfall time series of duration of five years.
362 Using a longer duration and smaller time step for the series would allow analysing the
363 evolution of the indicators at a given location. On top of this, the consequences of climate
364 change could be investigated. Since water work systems are long term investments, this
365 aspect of the issue should be studied very carefully. Further investigation should be performed
366 to analyse the effect of sizing the tank from the viewpoint of the water suppliers. This would
367 consist in applying standard techniques such as the “percentage rate of change of an
368 indicator” (see Aquacycle users manual), not according to water saving efficiency as it is
369 usually done, but to the reliability indicators.

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

376

377

378 **Acknowledgments**

379

380 We greatly acknowledge Cécile Huet (ENSG) for her help in drawing the maps with a
381 geographical information system, and Saskia de Longvilliers, Jean-Claude Deutsch and Bruno
382 Tassin for their advice.

383

384 **References**

385

386 C.I.EAU (Centre d'Information sur l'Eau), 2007, *54 questions pour "tout" savoir sur l'eau*,
387 C.I.Eau

388 COOMBES P. J., ARGUE J. R., KUCZERA G., 1999, "Figtree Place: a case study in water
389 sensitive urban development (WSUD)", *Urban Water* (1): 335-343

390 COOMBES P. J. and KUCZERA G., 2001, "Rainwater tank design for water supply and
391 stormwater management", *Stormwater Industry Association 2001 Regional Conference, Port*
392 *Stephens, NSW*

393 COOMBES P. J., Barry M.E. 2007a, "The effect of selection of time steps and average
394 assumptions on continuous simulation of rainwater harvesting strategies", *Water Science and*
395 *Technology*, Vol 55, No 4, 125-133

396 COOMBES P. J., 2007b, "Energy and economic impacts of rainwater tanks on operation of
397 regional water systems", *Australian Journal of Water Resources*, Vol 11, No 2, 177-1990

398 COWDEN J., WATKINS D. W., MIHELICIC J.R., 2008, "Stochastic rainfall modeling in West
399 Africa: Parsimonious approaches for domestic rainwater harvesting assessment", *Journal of*
400 *Hydrology*, 361, 64– 77

401 DE GOUELLO B., BERTHINEAU B., CROUM I., FRANÇOIS C., 2005, L'utilisation de l'eau de
402 pluie dans le bâtiment. Les résultats d'opérations expérimentales en France, *Annales du*
403 *Bâtiment et des Travaux Publics* (3) : 13-20.

404 FEWKES A., BUTLER D., 2000, "Simulating the performance of rainwater collection systems
405 using behavioral models", *Building Services Engineering Research and Technology*, 21(2):
406 99-106

407 FEWKES A., 1999, "Modelling the performance of rainwater collection systems: towards a
408 generalised approach", *Urban Water* (1): 323-333

409 GHISI E., MONTIBELLER A., SCHMIDT R. W., 2006, "Potential for potable water savings by
410 using rainwater: an analysis over 62 cities in southern Brazil", *Building and Environment*
411 (41): 204-210.

412 GHISI E., 2006, "Potential for potable water savings by using rainwater in the residential
413 sector of Brazil", *Building and Environment* (41): 1544-1550.

414 HERRMANN TH., SCHMIDA U., 1999, "Rainwater utilisation in Germany: efficiency,
415 dimensioning, hydraulic and environmental aspects", *Urban Water* (1): 307-316

416 JENKINS D., PAERSON F., MOORE E., SUN J.K., VALENTINE R., 1978, "Feasibility of rainwater
417 collection systems in California", *Contribution No. 173*. Californian Water Resources
418 Centre, University of California

419 LUCAS S.A., COOMBES P.J., HARDY M.J., GEARY P.M., 2006, "Rainwater harvesting, revealing
420 the detail", *Journal of the Australian Water Association*, Nov 2006, 89-94

421 MITCHELL, V.G., MEIN, R., MCMAHON, T.A., 2001, "Modelling the Urban Water Cycle",
422 *Journal of Environmental Modelling and Software*, 16 (7) 615-629

423 MITCHELL, V.G., MEIN, R., MCMAHON, T.A., 2003, "UVQ: Modelling the urban Movement
424 of Water and Contaminants through the Total Urban Water Cycle", In *28th International*
425 *Hydrology and Water Symposium*, 10-14 November, Wollongong, Australia

426 MITCHELL, 2005, "Aquacycle user guide" *Cooperative Research Centre for Catchment*
427 *Hydrology*, <http://www.toolkit.net.au/Tools/Aquacycle>

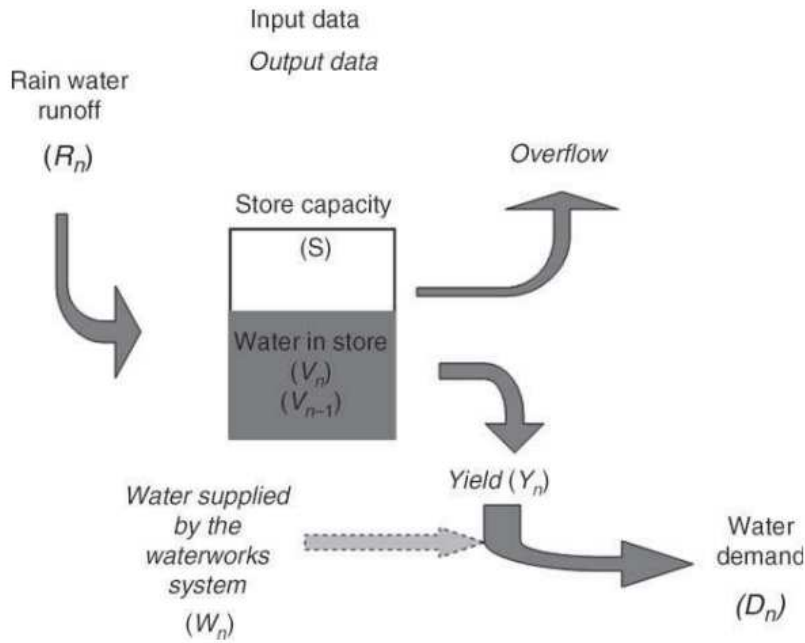
428 NOLDE E., 2007, "Possibilities of rainwater utilisation in densely populated areas including
429 precipitation runoffs from traffic surfaces", *Desalination*, 215: 1-11.

430

431

432

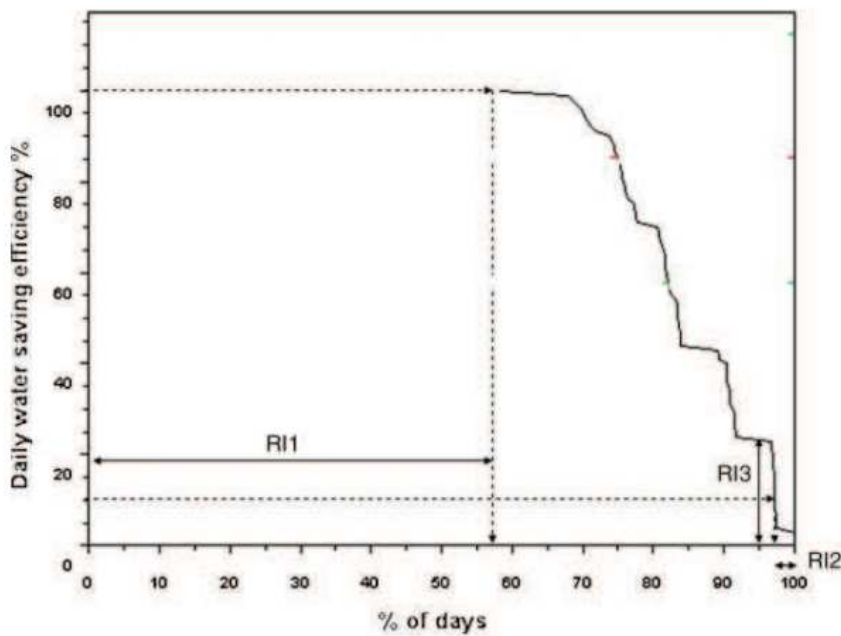
433 **Figures**



434

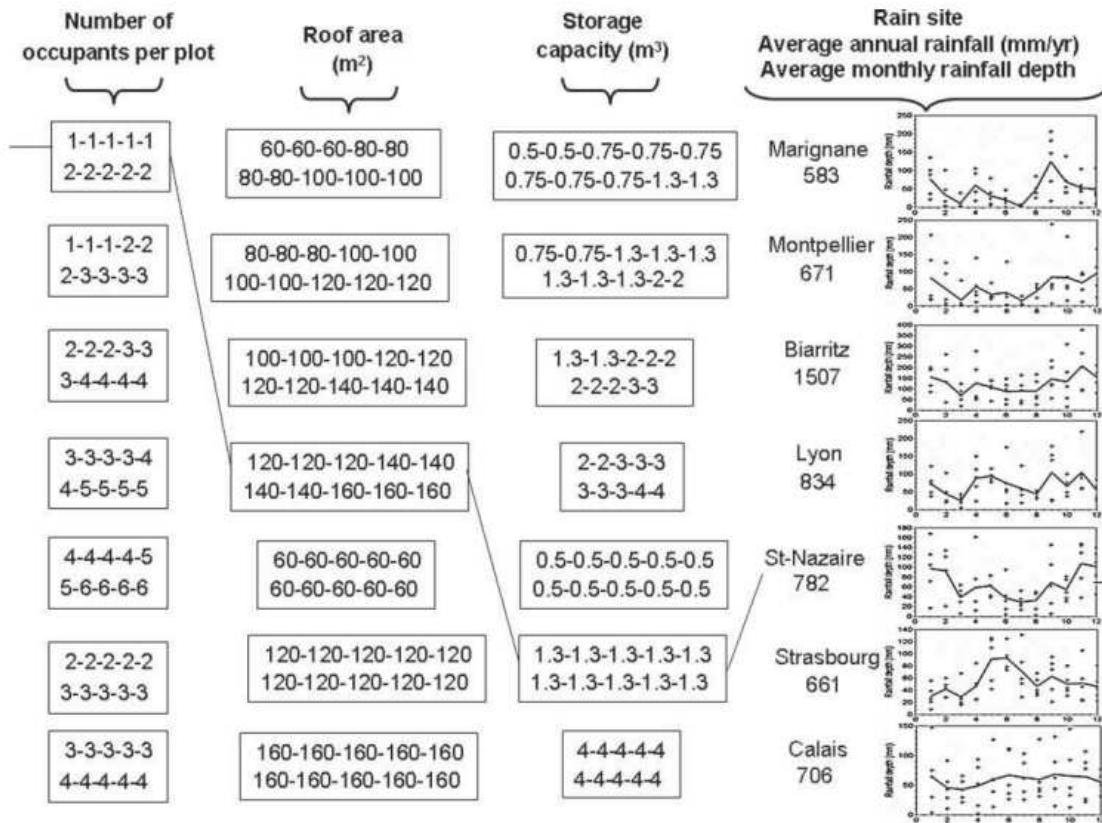
435 Fig 1: Description of a rainwater collection system

436



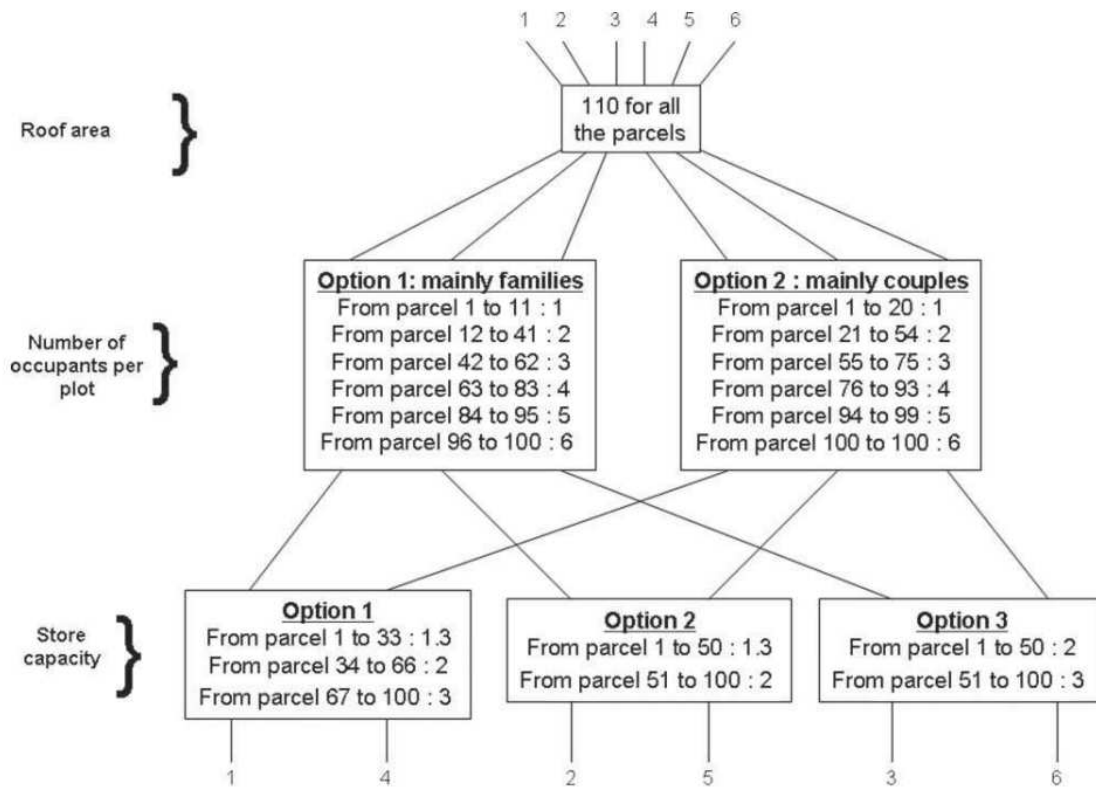
437

438 Fig 2: Example of a reliability curve for a simulation of a housing estate of 100 plots with the
 439 population distribution of the couples option, a roof area of 110 m² for all plots, a storage
 440 capacity of 1.3 m³ for all plots, and a rainfall series from Saint-Nazaire (West of France).



441

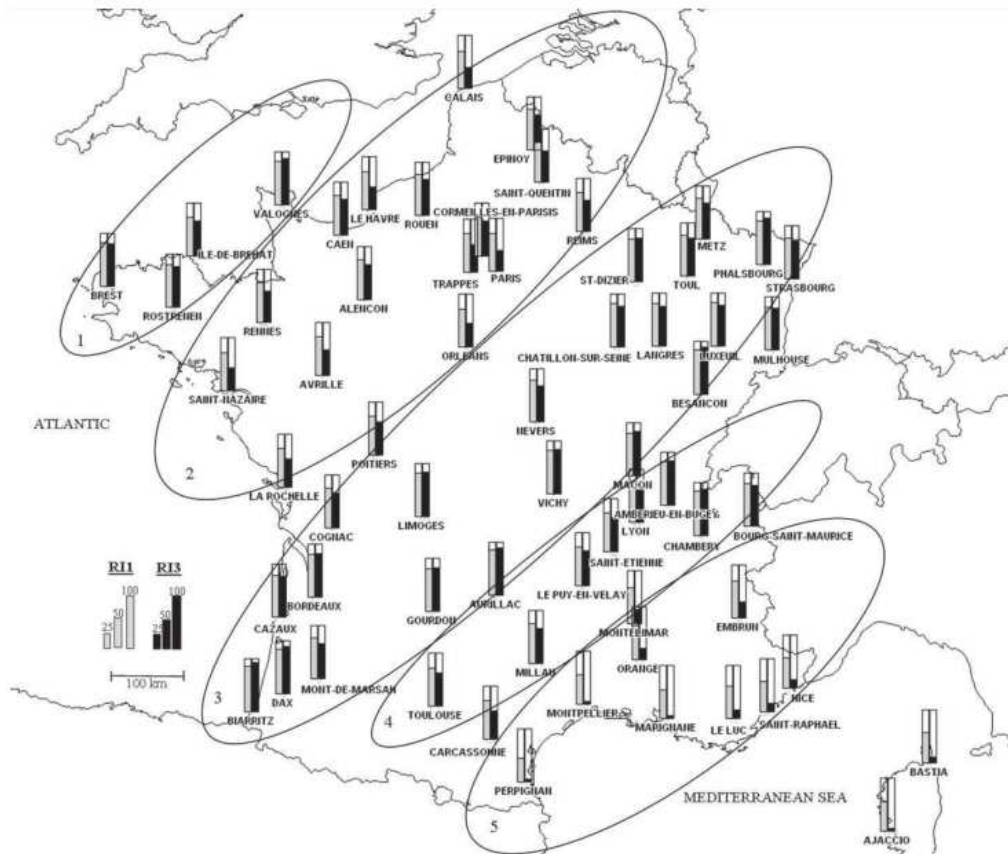
442 Fig 3: The chosen options to analyse the variability generated by each input. The modelled
 443 housing estate consists of 10 plots. For each input, 7 options were defined, in turn defining
 444 7*7*7*7 scenarios. Defining a scenario consists in selecting one option for each input, as it
 445 can be seen in the example.



446

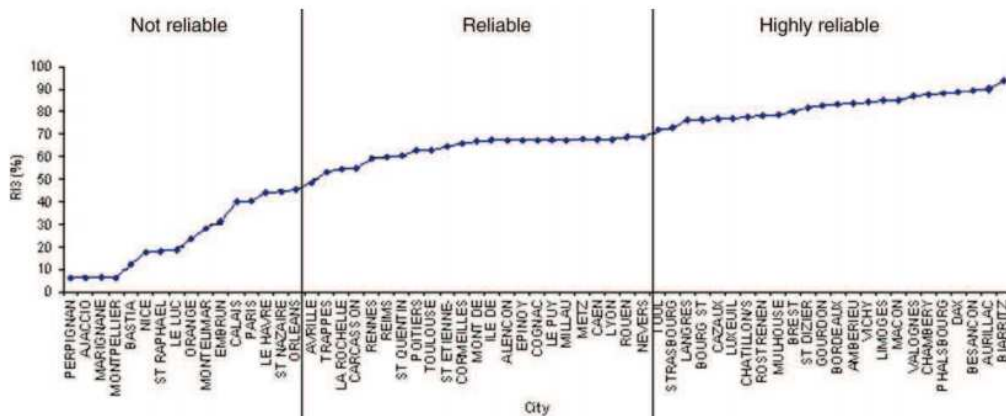
447 Fig 4: Definition of the chosen scenarios to perform the geographical analysis. The modelled
 448 housing estate consists of 100 plots. Three options were defined for the storage capacity, one
 449 for the roof area, and 2 for the number of people per plot. Therefore 6 scenarios (=3*1*2*1)
 450 were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

451



452

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



457

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

460

461 **Tables:**

462

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

468

	Mainly families option	Mainly couples option
469		
470	The houses	
471	Number of houses	479 2233
472	% of individual houses	91.2 87.7
473	The occupants	
474	% of house with 1 people	10.7 19.5
475	% of house with 2 people	29.6 34.3
476	% of house with 3 people	21.1 20.8
477	% of house with 4 people	20.8 17.6
478	% of house with 5 people	12.5 6.1
479	% of house with 6 people or more	5.3 1.4

480

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

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

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

487

488

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

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

496

497

498 Table 4: Statistics of the indicators, evaluated in the Paris area for 6 rainfall time series lasting
 499 5 years between 1975 and 2006

500

501		E	RI1	RI2	RI3
502	Mean	94.7	74.2	0.8	60.9
503	Standard deviation	1.3	2.3	0.6	10.7
504	Minimum	93.4	72.0	0.3	46.4
505	Maximum	96.4	78.0	1.6	71.2
506	1976–2005	94.8	74.4	0.7	66.8

507

508