

Retention performance of green roofs in representative climates worldwide

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14 **ABSTRACT**

15

16 The ongoing process of global urbanization contributes to an increase in stormwater runoff from
17 impervious surfaces, threatening also water quality. Green roofs have been proved to be innovative
18 stormwater management measures to partially restore natural states, enhancing interception,
19 infiltration and evapotranspiration fluxes. The amount of water that is retained within green roofs
20 depends not only on their depth, but also on the climate, which drives the stochastic soil moisture
21 dynamic. In this context, a simple tool for assessing performances of green roofs worldwide in
22 terms of retained water is still missing and highly desirable for practical assessments.

23 The aim of this work is to explore retention performances of green roofs as a function of their
24 depth and in different climate regimes. Two soil depths are investigated, one representing the
25 intensive usual configuration and another representing the extensive one. The role of the climate in
26 driving water retention has been represented by rainfall and potential evapotranspiration dynamics.
27 A simple conceptual weather generator has been implemented and used for stochastic simulation of
28 daily rainfall and potential evapotranspiration. Stochastic forcing is used as an input of a simple
29 conceptual hydrological model for estimating long-term water partitioning between rainfall, runoff
30 and actual evapotranspiration. Coupling the stochastic weather generator with the conceptual
31 hydrological model, we assessed the amount of rainfall diverted into evapotranspiration for
32 different combinations of annual rainfall and potential evapotranspiration in five representative
33 climatic regimes. Results quantified the capabilities of green roofs in retaining rainfall and
34 consequently in reducing discharges into sewer systems at an annual time scale. The role of
35 substrate depth has been recognized to be crucial in determining green roof retention performances,
36 which in general increase from extensive to intensive settings. Looking at the role of climatic
37 conditions, namely annual rainfall, potential evapotranspiration and their seasonality cycles, we
38 found that they drive green roof retention performances, which are the maxima when rainfall and
39 temperature are in phase.

Finally, we provide design charts for a first approximation of possible hydrological benefits deriving from the implementation of intensive or extensive green roofs in different world areas. As an example, 25 big cities have been indicated as benchmark case studies.

1. Introduction

The continuous growth of impervious surface areas leads to increased downstream flows with critical consequences for the functioning of existing sewer systems and triggers water quality degradation in receiving water bodies (Carter and Jackson, 2007; Carter and Rasmussen, 2006). A variety of management practices have been proposed to limit the environmental pressures associated with the altered hydrology of urban areas. In this context, green roofs are an innovative solution for mitigation of the impact of stormwater runoff, with the advantage of recovering green spaces, while preserving environmental quality (Getter and Rowe, 2006). Green roofs are indeed a valid alternative to traditional stormwater design and a low impact development practice (Dietz, 2007). Several authors recommend the use of vegetative roofs as an attractive stormwater management practice in urban watersheds, in order to reproduce the benefits produced by the interception and evapotranspiration processes in the natural water cycle, as in less disturbed environments. Green roofs are now quite familiar in Europe and North America: some cities have built green roof pilot projects and adopted incentives for applying green roof practices (Dvorak and Volder, 2010), while standards and guidelines are also being set up.

Several environmental benefits can be associated with green roofs, mainly related to the reduction of building energy consumption, mitigation of urban heat island effect, improvement of air quality, water management, increase of sound insulation, and ecological preservation (Berardi and Ghaffarian Hoseini, 2014). An important benefit related to green roofs is that they can efficiently detain and retain stormwater when compared to conventional roofs. In the following we

65 analyze some scientific studies aimed at the evaluation of hydrological performances of green roofs
66 by distinguishing between field experiments and modelling approaches.

67 Many field experiments have been carried out in order to understand the hydrological behaviour
68 of green roofs and to quantify the water-related benefits in specific climatic and physical
69 conditions. An interesting case has been proposed by Carter and Rasmussen (2006): a paired green
70 roof-black roof test plot was constructed at the University of Georgia (USA) and monitored for one
71 year for the effectiveness of the green roof in reducing stormwater flows. Green roof precipitation
72 retention decreased with precipitation depth; ranging from about 90 percent for small storms to
73 slightly less than 50 percent for larger storms. Moreover, they also found that runoff from the green
74 roof was delayed and that the average runoff lag times increased.

75 Bengtsson et al. (2005) studied a thin extensive green roof and its water balance in southern
76 Sweden. They observed that runoff from the green roof is substantially reduced when compared to
77 the runoff from black roofs because of evapotranspiration. As a physical interpretation of the water
78 dynamics within the green roof, they associated the beginning of runoff with the condition of soil
79 moisture reaching or exceeding the field capacity, and estimated the consequent runoff as equal to
80 the precipitation excess. They argued that the daily runoff dynamics could be described as a
81 function of daily precipitation, potential evaporation and storage capacity of the green roof.

82 Czemieli Berndtsson (2010) made a critical review of green roof performances on the basis of
83 results from full-scale installations as well as from laboratory models and looked for factors
84 affecting runoff dynamics. He concluded that geometrical properties (mainly slope), climate
85 (mainly rainfall) and vegetation (its age) are fundamental in determining runoff from green roofs.

86 Feng et al. (2010) quantified the energy balance components within an extensive green roof
87 installation in the South China University of Technology in Guangzhou (China). They found that,
88 without water limitations, incoming solar radiation was diverted into evapotranspiration of the
89 plant-soil system (60%), long-wave radiation exchange between the canopy and the atmosphere
90 (30%) and net photosynthesis of plants (10%).

91 Performances of green roofs have been also investigated in the Mediterranean climate by Fioretti
92 et al. (2010) with two full-scale experiments in north-west and central Italy. They concluded that
93 green roofs significantly mitigate storm water runoff generation in terms of runoff volume
94 reduction, peak attenuation and increase of concentration time, although reduced performance
95 could be observed during high precipitation periods. Under sub-tropical climate conditions, Voyde
96 et al. (2010) analyzed field monitoring results from a large extensive green roof in Auckland, New
97 Zealand (NZ). They found that the green roof retained about 82% of rainfall received per rainfall
98 event, with a median peak flow reduction of 93% compared to rainfall intensity. Similarly to other
99 studies, also Voyde et al. (2010) individuated in rain depth, rain intensity, climatic variables and
100 antecedent dry days the main key factors influencing the hydrology of green roofs.

101 DeNardo et al. (2005) studied a green flat roof at Rock Springs, Pennsylvania (USA). They
102 observed a range of rainfall retention from 19% to 98% in seven storms and peak runoff delayed by
103 2 hours. The effect of slope on extensive green roof stormwater retention was instead analyzed by
104 Getter et al. (2007) using 12 extensive green roof platforms constructed at the Michigan State
105 University (USA). They demonstrated that the lower the slope the higher the retention, with an
106 average retention value of about 80%.

107 Monterusso et al. (2004) analyzed runoff from four commercial green roof systems containing
108 three distinct vegetation types at the Michigan State University (USA). Rainfall retained during
109 their experiments ranged from 39% to 58%. It is worth noticing that their results highlight how
110 differences in water retention can be attributed to substrate depth, rather than drainage system or
111 vegetation type.

112 Two studies made in the UK by Stovin (2010) and Stovin et al. (2012) demonstrated the
113 important role of mean rainfall intensity, rainfall depth and an antecedent dry weather period,
114 which conditions antecedent moisture conditions. The latter is indeed crucial in determining the
115 performance of green roofs, in terms of retentions, peak attenuation and delay under extreme
116 rainfall conditions.

117 If field experiments, as briefly referred to above, allow the underlying physical processes to be
118 understood, modelling approaches permit phenomena to be mimicked, and consequently to
119 simulate green roof performances even in unmonitored conditions. Hydrological modelling
120 demonstrated that widespread green roof implementation can significantly reduce peak runoff rates,
121 particularly for small storm events (Carter and Jackson, 2007).

122 Hilten et al. (2008) modelled stormwater runoff data from green roofs with the HYDRUS- 1D
123 model (Šimůnek et al., 2008) in order to determine peak flow, retention and detention time for
124 runoff. Storm data were collected on a green roof in Athens, Georgia, USA, and used to calibrate
125 HYDRUS-1D simulated runoff. The study site consisted of a 37 m² modular block green roof
126 containing engineered soil and vegetation including several sedum species. Simulations explicated
127 the role of rainfall depth in determining water retention: in fact small storms are fully retained
128 while larger storms are partially attenuated.

129 The work carried out by Palla et al. (2009) advanced the understanding of the unsaturated water
130 flow in the coarse-grained porous media usually employed in green roofs. Using a bidimensional
131 model based on Richards' law and the Van Genuchten-Mualem functions they were able to simulate
132 the variably saturated flow within the green roof system with a satisfactory reproduction of
133 hydrograph main features, i.e. total discharged volume, peak flow, hydrograph centroid and water
134 content. In a later study, the same authors compared the performances of HYDRUS-1D with those
135 obtained by a conceptual linear reservoir in reproducing the hydrologic response of a green roof
136 system within the urban environment (Palla et al., 2012). They found that, comparing simulations
137 with observations from a field site in Genova, Italy, the HYDRUS-1D model resulted more
138 accurate. However, prediction errors of the conceptual model were still limited, so that outflow
139 hydrographs in terms of both total effluent volume and hydrograph shape were predicted with
140 acceptable accuracy.

141 While most of the previous mentioned studies focused on event scale or short time windows,
142 there are few examples in literature of long-term green roof performance evaluations, mainly
143 approached with hydrological models. An interesting study in this context was proposed by Stovin
144 et al. (2013). Namely, they used a conceptual hydrological flux model for the long term continuous
145 simulation of retention performances of extensive green roofs at 4 locations in the UK, with
146 different annual rainfall (ranging from 500 to 2700 mm/year) and potential evapotranspiration
147 (from 618 to 700 mm/year). A long term analysis was also performed by Carson et al. (2013) who
148 simulated extensive green roof performances in NY using an empirical model, calibrated against
149 observations and forced by historical rainfall (1971-2010). Locatelli et al. (2014) used a
150 deterministic lumped rainfall–runoff conceptual model to simulate the hydrological response of
151 green roofs during a 22-year (1989–2010) continuous simulation with Danish climate data. Cipolla
152 et al. (2016) used field data to calibrate and validate a numerical model, namely the commercial
153 software SWMM 5.1, to simulate the long-term hydrologic response of an extensive green roof.

154 Although the growing interest in the adoption of green roofs has attracted the attention of many
155 researchers who focused on the crucial hydrological phenomena emerging from field observations
156 and the hydrological modeling problem, as briefly reviewed above, many studies were restricted to
157 specific areas of interest. In this framework, results presented in this manuscript aim to quantify
158 retention performances of green roofs worldwide, considering several climatic conditions. In order
159 to do that a simplified stochastic weather generator has been proposed and described in Section 2.1.
160 This model has been designed to mimic daily rainfall and potential evapotranspiration in different
161 climates. In particular, it is able to reproduce stationary or seasonal forcings, which in turn have
162 been used to feed a simple conceptual green roof model, which is described in Section 2.2. The role
163 of soil substrate in governing water retention at an annual time scale has been investigated
164 considering an intensive and an extensive configuration. Results have been summarized in Section
165 3, where design charts for different climatic conditions are also provided for a rapid first
166 approximation estimate of green roof retention performances worldwide.

167 **2. Methods**

168 **2.1 Weather generator**

169 The use of a weather generator has always been related to the need of producing indefinitely
170 long synthetic weather series by simulating key properties of observed meteorological records
171 (Wilby, 1999). The pioneering idea of using Poisson point process and clustered point processes to
172 simulate the occurrences of rainfall events at different time scales dates back to the eighties
173 (Rodríguez-Iturbe et al., 1987a; Rodríguez-Iturbe et al., 1987b). During the last thirty years, in
174 order to capture and reproduce rainfall properties better across wide ranges of temporal and spatial
175 scales, there has been considerable research in the field of rainfall modelling using stochastic point
176 processes, which can be mainly classified as Neyman-Scott and Barlet-Lewis model types (see e.g.
177 Burlando and Rosso, 1991; Cowpertwait et al., 2002; Cowpertwait et al., 1996; Cowpertwait, 1991;
178 Cowpertwait and O'Connell, 1997; Entekhabi et al., 1989; Islam et al., 1990; Puente et al., 1993;
179 Verhoest et al., 1997 among others). Sometimes however, for sake of simplicity or analytical
180 tractability, the temporal structure within each rain event has been ignored and the marked Poisson
181 process representing precipitation has been physically interpreted at a daily time scale, where the
182 pulses of rainfall correspond to daily precipitation assumed to be concentrated at an instant in time
183 (Laio et al., 2001). We followed this last approach and integrated it with a simple parametric
184 representation proposed by Milly (1994) to describe the essential features of the annual land surface
185 hydrologic forcings. The model assumes that the seasonality of climate is mainly driven by the
186 seasonality of the solar irradiance normal to the top of the atmosphere, which produces a strong
187 signal with a dominant period of one year in most climatic variables. Precipitation and potential
188 evapotranspiration time series have been thus simulated as stochastic processes with expected
189 values modelled with annual harmonics, according to main climatic features observed in 10,000
190 observational sites worldwide.

191 The occurrence of rainfall R at time t is idealized as a series of events at a daily time scale,
 192 arising from a non-stationary and cyclic Poisson point process with parameter $1/\lambda$ (rate of the
 193 Poisson process occurrences, [1/days]) and whose interarrival time $\lambda(t)$ [days] is here modeled
 194 through a cyclic sinusoidal function, with 1-year period, according to the following equation:

$$195 \quad \lambda(t) = \bar{\lambda} \left[1 + \delta_{\lambda} \sin \left(\frac{2\pi t}{365} + \omega_{\lambda} \right) \right] \quad (1)$$

196 where $\bar{\lambda}$ is the average interarrival time [days] between rainfall events, the standardized semi-
 197 amplitude δ_{λ} is the ratio between the semi-amplitude of the annual harmonics of $\lambda(t)$ and the
 198 annual average (i.e. $\bar{\lambda}$), while ω_{λ} is the initial phase.

199 Rainfall rates during each event are assumed to be a random process described by an exponential
 200 distribution, with mean $\alpha(t)$ [mm/day] described as follows:

$$201 \quad \alpha(t) = \bar{\alpha} \left[1 + \delta_{\alpha} \sin \left(\frac{2\pi t}{365} + \omega_{\alpha} \right) \right] \quad (2)$$

202 where $\bar{\alpha}$ is the average amount of rainfall [mm/day], the standardized semi-amplitude δ_{α} is the ratio
 203 of the semi-amplitudes of the annual harmonics of $\alpha(t)$ to the annual average (i.e. $\bar{\alpha}$), and ω_{α} is the
 204 initial phase.

205 Potential evapotranspiration $ET_p(t)$ [mm/day] has been modelled with a harmonic as follows:

$$206 \quad ET_p(t) = \overline{ET_p} \left[1 + \delta_E \sin \left(\frac{2\pi t}{365} + \omega_E \right) \right] \quad (3)$$

207 where $\overline{ET_p}$ is the average annual potential evapotranspiration [mm/day], the standardized semi-
 208 amplitude δ_E is the ratios of the semi-amplitude of the annual harmonics of $ET_p(t)$ to the annual
 209 average (i.e. $\overline{ET_p}$), and ω_E is the initial phase.

210 We decided to reduce the degrees of freedom of this analysis to simulate green roof
 211 performances at an annual time scale as a function of only two climatic variables (i.e. \bar{P} and $\overline{ET_p}$)
 212 while keeping the problem as simple as possible. In order to do that, it is worth noting that the same
 213 expected annual precipitation \bar{P} [mm/year] can be obtained by the infinite combination of $\bar{\alpha}$ and $\bar{\lambda}$,
 214 as shown e.g. in Figure 1. Thus we decided to keep constant the mean interarrival time $\bar{\lambda}$ for all the

215 simulated climatic conditions while exploring the variability of $\bar{\alpha}$; consequently, different values of
216 \bar{P} will be obtained using the stochastic model of equations (1) and (2).

217 In order to apply our model with a reliable parametrization in different climatic conditions, we
218 explored the parameter space by fitting Equations (1)-(3) to observed time series downloaded by
219 the GHCN (Global Historical Climatology Network, [https://www.ncdc.noaa.gov/oa/climate/ghcn-](https://www.ncdc.noaa.gov/oa/climate/ghcn-daily/)
220 [daily/](https://www.ncdc.noaa.gov/oa/climate/ghcn-daily/)) database, which pooled daily climate data from land surface stations across the globe. We
221 focused the attention on daily precipitation and temperature data, using the 10,000 stations with
222 longest time series. The location of the selected stations is reported in Figure 2.

223 With reference to rainfall, daily data from each station have been first analyzed at a monthly
224 time scale in order to determine the average rainfall amount α on wet days, the mean number of
225 occurrences and consequently the rate of the Poisson process $1/\lambda$ (estimated as the number of rainy
226 days divided by the days in the month). The average values $\bar{\alpha}$ and $\bar{\lambda}$ have been thus estimated as the
227 arithmetic mean from the monthly time series. For each year, the semi-amplitudes of the annual
228 harmonic of α and λ have been computed as the half of the difference between maximum and
229 minimum values assumed at a monthly time scale. Parameters δ_λ and δ_α have been finally
230 estimated as the ratio between the mean of semi-amplitudes over all years and annual averages $\bar{\alpha}$
231 and $\bar{\lambda}$. Estimated parameters $\bar{\lambda}$, δ_λ , $\bar{\alpha}$, δ_α , for all the 10,000 considered stations, have been reported
232 as histograms in Figure 3a, b, c, d.

233 Daily temperature data have been used to obtain potential evapotranspiration also taking into
234 account solar insolation at the selected stations. Specifically, for each station, temperature
235 observations have been averaged at a monthly time scale and then a monthly ET_p time series has
236 been assessed by a simplified procedure as a function of temperature and station latitude
237 (Thornthwaite, 1948). Similarly to eq. (1) and (2), for parameterization of eq. (3) average value $\overline{ET_p}$
238 has been estimated as the mean of monthly ET_p time series in each station, while the standardized
239 semi-amplitude δ_E has been estimated as the ratio between the mean of semi-amplitudes over all

240 years and annual average $\overline{ET_p}$. Figure 3e shows annual averages $\overline{ET_p}$ obtained in the selected
241 locations and reveals a quite symmetric distribution, while the standardized semi-amplitude δ_E of
242 the annual harmonic is shown in Figure 3f.

243 As anticipated, we decided to keep $\bar{\lambda}$ constant for all simulations in order to keep the degree of
244 freedom of the problem low. On the basis of our investigations, we assumed $\bar{\lambda}$ equal to 4.35 days,
245 that is the median value observed in the 10,000 considered stations (Figure 3a). We then considered
246 five representative climatic regimes, hereafter named also cases, keeping constant rainfall rates and
247 potential evapotranspiration during the hydrological year, or only one of the two, or considering
248 both cyclic (in phase or in counter-phase). With the same intention to keep our set up simple, cyclic
249 time series have been built keeping constant also the standardized semi-amplitudes of λ , α and ET_p ,
250 that have been chosen as the median of their empirical distributions, i.e. $\delta_\lambda = 0.45$, $\delta_\alpha = 0.35$, $\delta_E =$
251 0.30 . Estimated parameters have been summarized in Table 1, where they are combined in order to
252 depict five different climatic regimes.

253 The weather generator has been used to generate a 100-year-long rainfall and potential
254 evapotranspiration daily time series for all the possible combinations of $\bar{\alpha}$ and $\overline{ET_p}$ for each
255 climatic regime. Time series have been used as input to the conceptual hydrological model,
256 discussed below.

257

258 **2.2 Runoff model**

259 The hydrological conceptual model introduced by Viola et al. (2014) has been used in order to
260 simulate soil moisture dynamics in the soil layer and consequently an evapotranspirative flux and
261 runoff from green roofs. Although the model has been developed for natural river basins, slight
262 changes allow the conceptual scheme to be adapted to our setting, following a similar approach as

263 in former studies that applied conceptual models for simulating the hydrological behaviour of green
 264 roofs (Palla et al., 2012).

265 Three interconnected elements have been used: a soil bucket linked with two linear reservoirs,
 266 one accounting for the surface runoff component over the roofs, and another accounting for the
 267 leakage collection and restitution. The runoff contribution per unit area has been calculated at a
 268 daily time scale, considering the sewer connection as the basin outlet. The runoff over the green
 269 roofs, although they are usually designed to limit and possibly avoid it, has been modelled by
 270 saturation excess and then transferred to the sewer system through the surface reservoir with a
 271 transit time of a day. Water leaked from the top soil layer is ideally collected by a second reservoir
 272 characterized again by a residence time of one day. It is worth mentioning that although both the
 273 transit and residence times are certainly less than one day, they are both set to one day according to
 274 the time step of the adopted models.

275 The water input to the system is the daily rainfall depth, R [mm/day], which drives the relative
 276 soil moisture dynamics. Soil is characterized by porosity and by root depth, termed n and Z_r
 277 respectively, whose product, known also as “active soil depth”, will be used as a model parameter.
 278 The numerical solution of a simple balance equation, through a forward finite differences method,
 279 allows the calculation of soil moisture variation within the soil bucket during a daily temporal step.
 280 The runoff over the green roof (Q_s) occurs when rainfall exceeds the available storage capacity and
 281 is equal to the excess. The water losses due to evapotranspiration ET and leakage $L = (s - s_t)nZ_r$ are
 282 calculated at each time step as a function of the relative soil moisture (s) as follows:

$$283 \quad ET + L = \begin{cases} 0 & \text{if } s \leq s_0 \\ ET_p \left(\frac{s - s_0}{s_t - s_0} \right) & \text{if } s_0 < s \leq s_t \\ ET_p + (s - s_t)nZ_r & \text{if } s_t < s \leq 1 \end{cases} \quad (4)$$

284 where s_t has a role of field capacity and s_0 represents the wilting point. The evapotranspiration-
 285 leakage-soil moisture relation is modelled assuming that when relative soil moisture exceeds s_t ,

286 evapotranspiration occurs at the maximum rate, ET_p , while saturation water $(s - s_t)nZ_r$ is
 287 transferred instantaneously to the conceptual linear reservoir. Below s_t , no leakage occurs and
 288 evapotranspiration decreases linearly to zero for relative soil moisture equal to s_0 or less. As already
 289 pointed out by Viola et al. (2016), the relation in eq.(4) between the soil moisture and water losses
 290 is simple and parsimonious because it uses only three parameters, two characterizing the soil
 291 properties (s_t and s_0) and one representing the maximum (or potential) evapotranspiration rate ET_p .
 292 In order to take into account the influence of vegetation on water demand, a vegetational coefficient
 293 should be introduced. However, the virtual vegetation variability (as defined e.g. by Viola et al.
 294 (2014)) would introduce another degree of complexity to the problem; thus we preferred to consider
 295 a single vegetation type that will be used for both intensive and extensive green roofs.

296 The total runoff Q is simply computed as the sum of two contributions: the excess saturation
 297 surface runoff, Q_s , and the leakage, L . Each contribution is routed into a linear reservoir
 298 characterized by a one-day residence time.

299 Model outputs have been aggregated at a yearly time scale and then averaged to estimate an
 300 index of retention (IOR) defined as the ratio between actual evapotranspiration and rainfall for each
 301 100-year-long time series. This index can range between zero (no evapotranspiration, green roofs
 302 are ineffective) and one (all the rain is diverted into evapotranspiration, thus the green roof has a
 303 perfect efficiency in reducing water inputs to the sewer system). The IOR has been calculated in the
 304 five representative climatic regimes, introduced in section 2.1, and referring to two green roof
 305 configurations. The first is an extensive one, thus a thin layer of active soil (depth of 90 mm), while
 306 the second is an intensive configuration characterized by a deeper soil ($nZ_r = 450$ mm). Both the
 307 analyzed configurations have the same soil hydrological properties and same vegetation; thus the
 308 same parameters $s_0 = 0.30$ and $s_t = 0.85$ have been adopted in eq.(4) for both configurations.

309

3. Results

Each of the proposed representative climatic regimes, introduced in section 2.1, refers to a specific combination of rainfall and potential evapotranspiration during the hydrological year. For each case the influence of annual rainfall P (ranging from zero to 3000 mm/year) and potential evapotranspiration ET_p (ranging from zero to 2000 mm/year) in leading to annual water retention is explored with reference to extensive ($nZ_r = 90$ mm) and intensive ($nZ_r = 450$ mm) green roof configurations, and performances evaluated in terms of IOR for all the possible P - ET_p combinations are presented in Figure 4.

Table 1 reports the averages of the obtained IORs within the chosen domain of rainfall and potential evapotranspiration, in order to give an indicative performance score that is helpful in comparing the five representative climatic regimes,. Furthermore 25 cities have been proposed as benchmark examples. Each of these cities has been attributed to a given climatic case and from graphical analysis of Figure 4 it is possible to argue about green roof retention performances, for both intensive and extensive configurations, in those selected locations.

The first analyzed case refers to stationary conditions that can be considered as an ideal reference condition: rainfall statistics are supposed to remain unaltered within the hydrological year as well as potential evapotranspiration. Figure 4, central and right subplots in the first row, presents results in terms of IOR for the two analyzed soil configurations. The average retention observed for all the possible combinations of annual rainfall and potential evapotranspiration is 52.8% for the thin soil and 59.6% for the deep soil, confirming that intensive configurations are more effective in retaining water. This is obviously due to the higher active soil depth, which can store more water, reducing deep leakages and consequently allowing more water evaporation from soil and vegetation.

The second case is representative of zones where rainfall is almost constant during the hydrological year, but temperature and consequently potential evapotranspiration have one peak as it is, for instance, in oceanic climate. The green roof performances in these climatic conditions are

comparable to those obtained in the steady state case (see Table 1), results in terms of IOR for the two analyzed configurations are shown in Figure 4, second row. The city of New York falls in this climatic case: in fact the monthly rainfall is almost constant during the year (about 100 mm/month), while temperatures show seasonality, with a peak during the summer (about 23 °C in August) and a trough in winter (about 0° in January). From Figure 4 it is possible to extract the mean retention efficiency for extensive (i.e. $IOR = 0.55$) and intensive configuration (i.e. $IOR = 0.62$) for this city.

In the third case we summarized world areas where potential evapotranspiration could be considered constant through the hydrological year while rainfall shows seasonal patterns with one peak. This is the case for tropical climates. Retention performances in this case decrease: the average percentage of rainfall diverted into evapotranspiration is 49.9% for extensive green roofs and 57.2% for the intensive ones (see Table 1). This drop in performances, with respect to the ideal case 1, is explained by more runoff and leakage produced during the heavy rainfall periods. Results are shown in Figure 4, third row, and the city of Mumbai could be presented as the paradigm of this climatic situation. Temperature is almost constant during the year (27°C as daily mean), but rainfall is mostly concentrated during the monsoon period (from June to September). In this city, with this peculiar climate, the mean retention efficiency for intensive green roofs is equal to 0.34 while for extensive configurations is 0.41.

The world areas where both rainfall and temperature display seasonal cycles have been summarized in the last two cases. In case 4 we consider in-phase climatic forcings, meaning that when rain is high, the evapotranspiration demand is high, too. Such a condition occurs in humid subtropical climates. Performances in this case are again comparable with the ideal case 1 (see Table 1). Indeed when rainfall inputs increase also losses due to evapotranspiration increase, keeping soil moisture dynamics similar to those observed in the case 1. Figure 4, fourth row, depicts the IOR for all the explored combinations of annual rainfall and potential evapotranspiration for the two green roof configurations. Tokyo is one of the cities belonging to this case: the analysis of climatic statistics shows how the temperature has a seasonal behaviour,

362 with a peak in August (average daily mean of about 23°C) when rainfall has its maximum (about
363 280 mm/month). Results for this city reveal that extensive green roofs retain 48% of annual rainfall,
364 while intensive ones retain 56%.

365 The last case refers to areas where rainfall and potential evapotranspiration are in counter-phase
366 during the hydrological year, as happens with a Mediterranean climate. This climatic condition is
367 the worst in terms of retention performances, that are the lowest among the analyzed cases (0.47 for
368 extensive and 0.54 for intensive green roofs). The physical explanation for more runoff occurring in
369 such a climate is that when potential evapotranspiration is low, rainfall saturates the soil triggering
370 leakage and superficial runoff. Results are shown in Table 1 and Figure 4, fifth row. Among the
371 analyzed cities, Rome with hot summers (25 °C of daily mean in August) and mild rainy winters
372 (with more than 80% of rain falling from October to April), falls in this latter climatic case.

373 To give evidence of the reliable results provided by the design charts plotted in Figure 4, and
374 thus also of the overall good performances of the modelling approach adopted in this study, we
375 refer to the results presented by Stovin et al. (2013) and Carson et al. (2013), already described in
376 the introduction. Namely, we compared the index of retention as obtained by the mentioned authors
377 with those provided by our design charts in Figure 4. In particular, we first attributed each location
378 studied in Stovin et al. (2013) and Carson et al. (2013) to a climatic case, and then extrapolated the
379 main climatic conditions (i.e. mean annual rainfall and potential annual evapotranspiration) which
380 determined the performances of the analyzed green roofs. Then, we used the design charts in Figure
381 4 to calculate the IOR, referring to intensive or extensive configurations depending on the
382 considered case study. Results of these comparisons, which have been reported in Table 2, show a
383 good accordance in very different climatic conditions, with negligible discrepancies between
384 observations and modelled IORs which are mainly imputable to the different soil capacity
385 considered and can certainly be accepted under the assumptions and simplifications here made.

386

387 **4. Conclusion**

388 A worldwide assessment of retention efficiency of green roofs has been carried out and
389 presented in this study with the aim to provide information to scientists, practitioners and policy
390 makers involved in urban planning and interested in evaluating the possible hydrological impact of
391 green roofs in areas where this evaluation is tricky or impossible, due e.g. to the lack of climatic
392 data (rainfall and temperature) or the costs of field experiments. Specifically we designed a tool for
393 a first-approximate estimate of green roof retention performances in different climates with respect
394 to intensive and extensive configurations, by coupling a simple stochastic weather generator with a
395 conceptual model miming the hydrological behaviour of the green roof. Massive numerical
396 simulations have been carried out in order to generate rainfall and potential evapotranspiration time
397 series in different climates and afterwards to evaluate hydrological water fluxes through the two
398 green roof configurations.

399 Results highlight the role of soil depth and climate in driving the retention capacity of a green
400 roof. The amount of retained water increases with increasing soil depth, because more water is
401 allowed to be stored in the active soil and consequently more water can evaporate from soil and
402 vegetation. Regarding the climate, the performance of a green roof increases when rainfall and
403 potential evapotranspiration exhibit the same seasonality during the hydrological year (i.e. their
404 forcings are in-phase), as happens, for example in humid subtropical climates. Conversely, the
405 green roof presents the minimum efficiency when rainfall and potential evapotranspiration are in
406 counter-phase, as is found in a Mediterranean climate.

407 Moreover, we provided design charts for representative climates worldwide, which make it
408 possible to evaluate quickly green roof performances starting from easy-to-obtain data and climatic
409 information. Monthly rainfall and temperature distribution will guide the user in the choice of the
410 appropriate climatic case as a function of rainfall and temperature stationarity or seasonality within
411 a generic hydrological year. Then the annual mean value of rainfall and potential

412 evapotranspiration are the only required data in order to evaluate how much water is retained by the
413 green roof system, or conversely how much is released into the stormwater sewer system. Two
414 main green roof configurations have been explored, intensive and extensive: for both an evaluation
415 of the index of retention (ranging from 0, when all the rainfall is turned into runoff, to 1, when all
416 the rainfall is retained and evapotranspired) can be read from the corresponding design charts.

417 Further research efforts are needed in order to examine the role of rainfall extremes in driving
418 green roof retention and detection performances at temporal time scales shorter than a day, which
419 are crucial for sewer system design. This will be challenging for the complexity of extreme rainfall
420 statistics depending not only on site location but also on local conditions as topography or sea
421 distance.

422

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548 **Table**

	$\lambda(t)$			$\alpha(t)$			$ET_p(t)$			Index Of Retention	
	$\bar{\lambda}$	δ_λ	ω_λ	$\bar{\alpha}$	δ_α	ω_α	$\overline{ET_p}$	δ_E	ω_E	nZr	nZr
	[days]	[-]	[rad]	[mm/days]	[-]	[rad]	[mm/days]	[-]	[rad]	90 mm	450 mm
Case 1	4.35	0	0	Variable	0	0	variable	0	0	0.529	0.596
Case 2	4.35	0	0	Variable	0	0	variable	0.30	$-\pi/2$	0.518	0.590
Case 3	4.35	0.45	$-\pi/2$	Variable	0.35	$\pi/2$	variable	0	0	0.500	0.572
Case 4	4.35	0.45	$-\pi/2$	Variable	0.35	$\pi/2$	variable	0.30	$\pi/2$	0.519	0.585
Case 5	4.35	0.45	$-\pi/2$	Variable	0.35	$\pi/2$	variable	0.30	$-\pi/2$	0.471	0.545

549

550 **Table 1:** Weather generator parameters used in equations (1) - (3) to simulate the five climatic
551 regimes and index of retention (IOR) for the two green roof configurations analyzed.

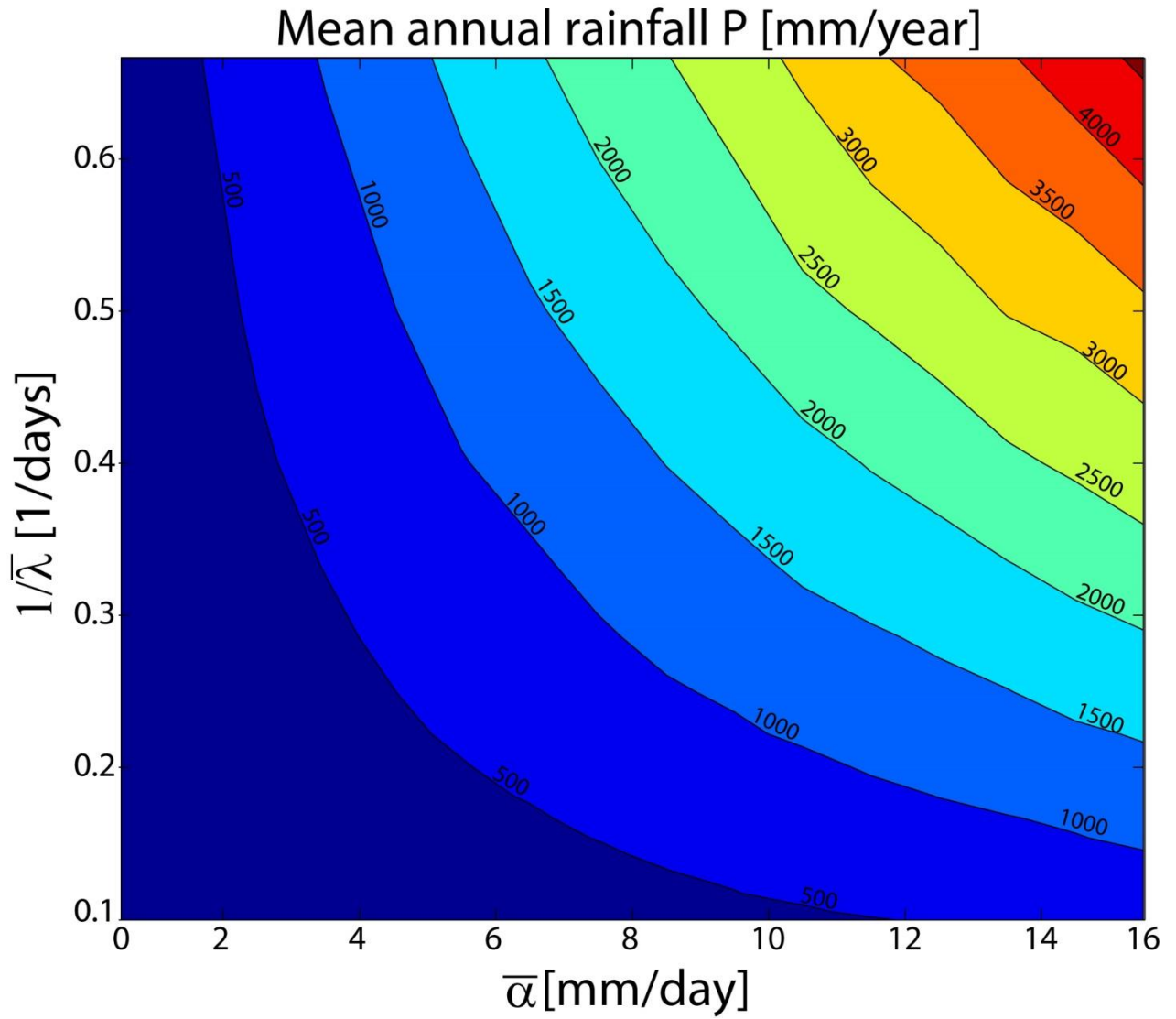
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Location	Case (1-5)	\bar{P} [mm/year]	$\overline{ET_p}$ [mm/year]	IOR from Stovin et al. (2013)* and Carson et al. (2013)**	IOR from Figure 4
NW Scotland	5	2700	620	0.19*	0.2
Sheffield	5	838	670	0.40*	0.5
Cornwall	5	1360	650	0.33*	0.4
East Midlands	2	500	700	0.59*	0.74
New York	2	1290	750	0.58**	0.55

Table 2: Comparison of green roof retention performances as resulted from literature studies and from the design charts given in Figure 4.

556

557 **Figures**

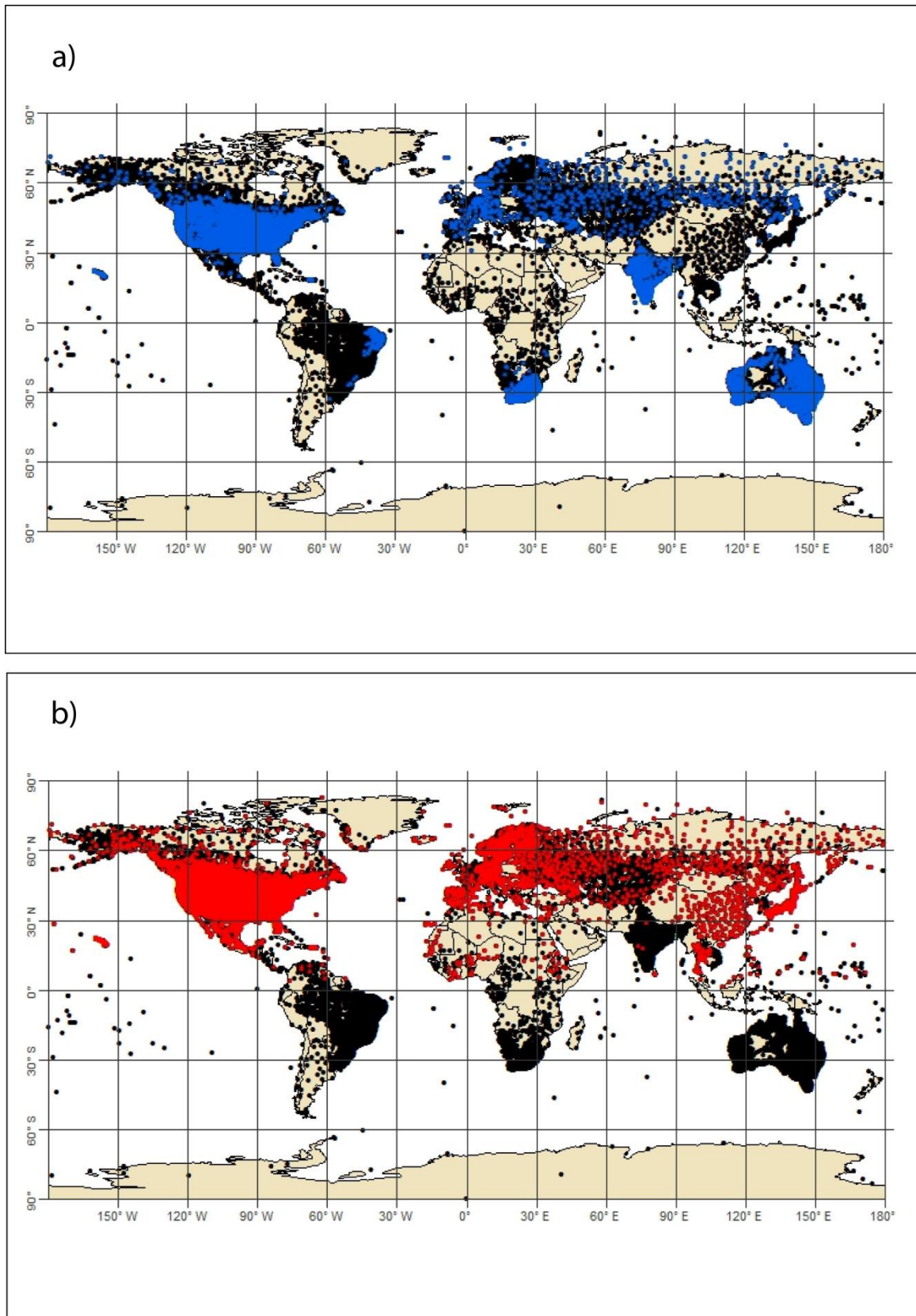


558

559 **Figure 1:** Expected annual rainfall depths as a function of average interarrival time $\bar{\lambda}$ and
 560 average amount of rainfall $\bar{\alpha}$ as obtained by integration of equations. (1) and (2) with parameters
 561 $\delta_\lambda=0.45$; $\delta_\alpha=0.35$; $\omega_\lambda=-\pi/2$; $\omega_\alpha=\pi/2$.

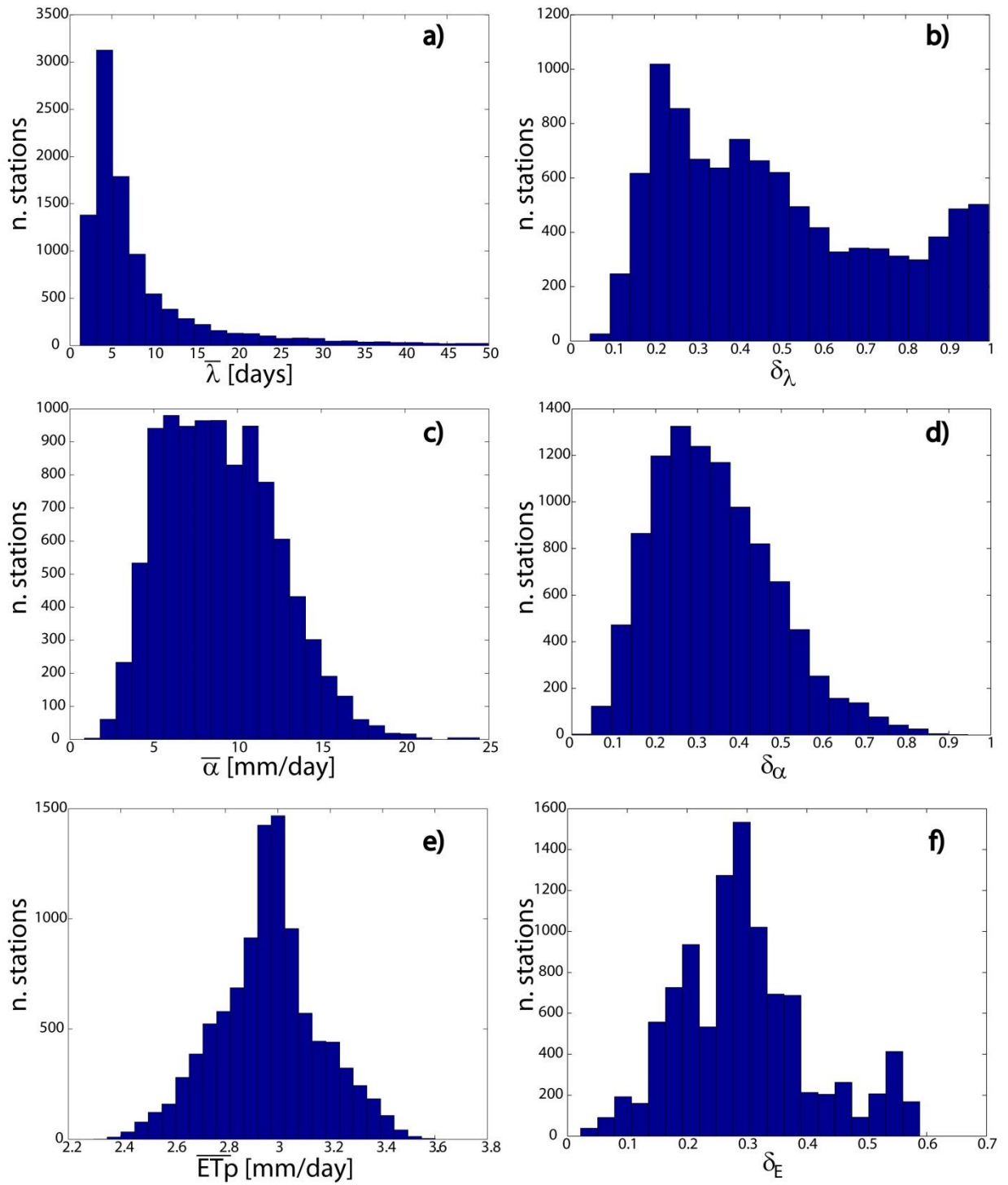
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565 **Figure 2:** Location of the 10,000 rainfall (a) and temperature (b) gauging stations used to
 566 parameterize the weather generator (Data from <https://www.ncdc.noaa.gov/oa/climate/ghcn-daily>)



569 **Figure 3:** Worldwide statistics from the 10,000 selected stations for: average rainfall interarrival
 570 time $\bar{\lambda}$ (a) and corresponding standardized semi-amplitude δ_{λ} (b); average amount of rainfall $\bar{\alpha}$ (c)
 571 and corresponding standardized semi-amplitude δ_{α} (d); average potential evapotranspiration $\overline{ET_p}$
 572 (e) and corresponding standardized semi-amplitude δ_E (f).

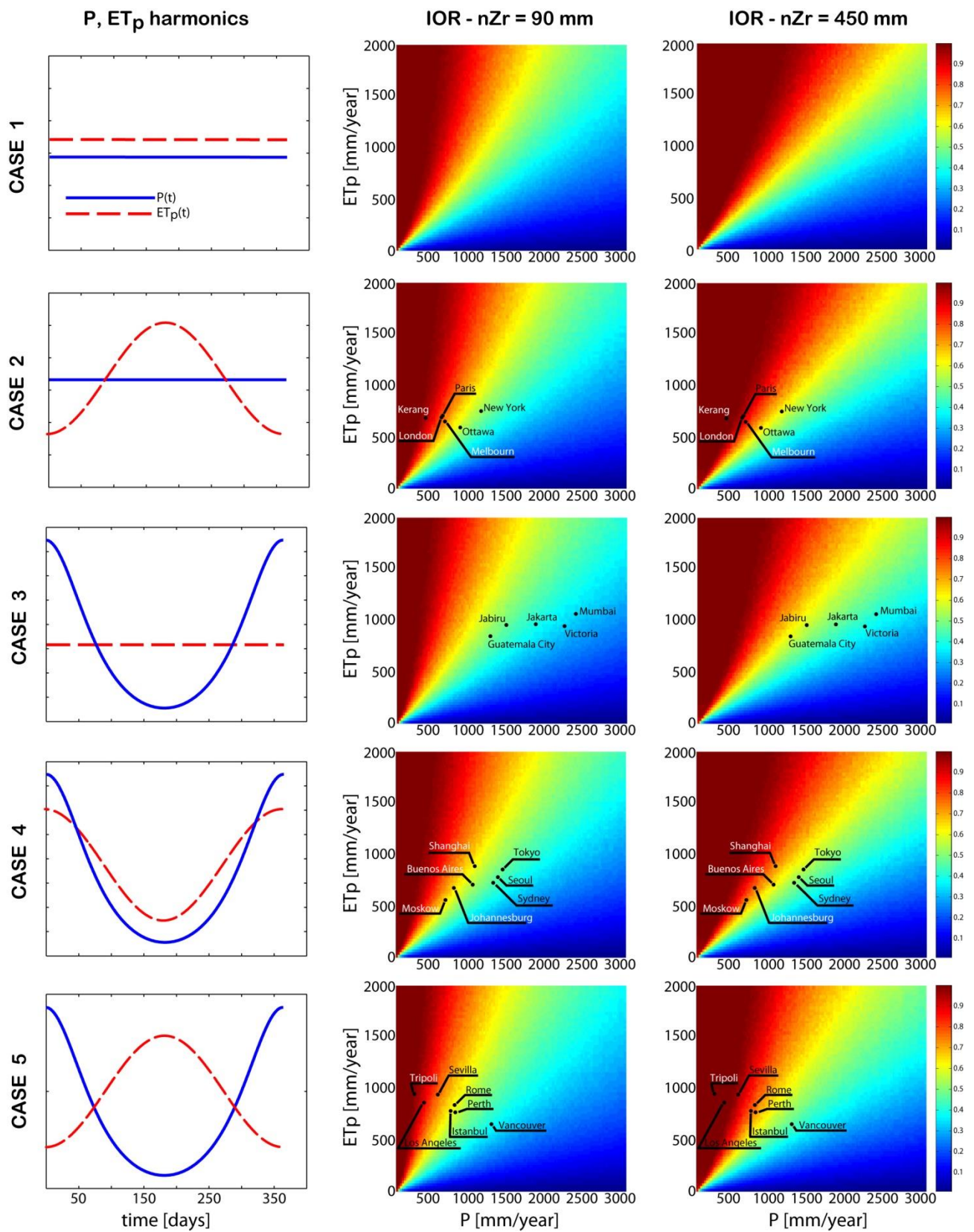


Figure 4: Green roof retention performances in different climates (first column) and for two active soil depths: second column refers to extensive configurations (i.e. $nZ_r = 90$ mm) while the

577 third column refers to intensive configurations (i.e. $nZ_r = 450\text{mm}$). Results are shown in terms of
578 index of retention IOR (\overline{ET}/\bar{P}), as a function of mean annual rainfall \bar{P} and mean annual potential
579 evapotranspiration \overline{ET}_p . Dots indicate climatic conditions for selected large cities, to show the
580 simple usage of the design charts for estimation of green roof performances.

581

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