

Parameters influencing run-off on vegetated urban soils: A case study in Marseilles, France

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31 Abstract

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In urban areas, episodes of extreme precipitation may generate run-off floods, but 33 urban soils are seldom considered in spatial planning documents. Our aim was to 34 assess the infiltration of vegetated urban soils and to identify the soil parameters 35 affecting infiltration in order to explore the potential of these soils for run-off 36 mitigation under a Mediterranean climate with extreme precipitation episodes. We 37 compared vegetated soils in the "urban" zone of the Marseilles' 16th district 38 39 (France) either lying on former clay quarries or tile factories (T) or not (NT) and 40 with different land-uses. We used a simplified method to measure field saturated hydraulic conductivity (K_{fs}), measured penetration resistance in the first 0.15 m 41 42 (Q_d) and analysed physico-chemical properties in the first horizon. Levels of runoff production were estimated according to K_{fs} and an adaptation of USDA 43 Hydrologic Soil Groups. All soils were Technosols or Anthrosols regardless of 44 their prior history. We found that land-use history influenced K_{fs}, with T soils and 45 soils with current vegetated land-use younger than 13 years having lower K_{fs} than 46 NT soils and soils with land-use older than 13 years. Soil organic matter content 47 influenced K_{fs} positively when soils were young, while vegetation cover and 48 penetration resistance (most of the soils had $Q_d > 2$ MPa) had not a clear effect on 49 K_{fs}. Overall, combining K_{fs} and soil depth, 14.3 % of the T soils and 84.6 % of the 50 NT soils had low levels of run-off production. It is therefore recommended that 1) 51 Technosols or Anthrosols should be characterised for their unique physico-52 chemical and physical properties but also for their land-use history, and 2) the 53 infiltration of these soils should be considered in spatial planning documents. 54

55 Keywords

56 Infiltration; Compaction; Run-off; Urban soils; Technosols; Tile industry;

1. Introduction

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Extreme precipitation episodes may affect urban areas. The intensity of these 60 episodes and poor infiltration in soils may generate run-off floods (Bhaduri et al., 61 2001; Chalvet and Claeys, 2011; Kundzewicz et al., 2014). These floods produce 62 63 substantial damage to the urban network, increase traffic jams and accidents, and are a source of pollution (Davis et al., 2001; Koetse and Rietveld, 2009; Yang and 64 Zhang, 2011). Several factors increase the risk of run-off flooding: (1) a higher 65 66 intensity of precipitations (Trenberth, 2011) and (2) urbanization (Kundzewicz et al., 2014). Urbanization jeopardizes the territory, reducing permeable surfaces such 67 68 as those found in French Mediterranean coastal zones (Robert et al., 2019). Urbanization also affects infiltration in soils since it contributes to compaction 69 70 (Gregory et al., 2006; Yang and Zhang, 2011; Shuster et al., 2014).

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One of the goals of planning documents is to tackle flood risks in order to reduce 72 73 both hazards and vulnerability. Water management strategies encourage the collection of stormwater to alleviate the hazard, either by adapting the sewer 74 75 network or using sustainable drainage systems (Perales-Momparler et al., 2015). 76 Spatial planning may also limit urbanization, but local planning practices can be 77 very uneven, as shown in Southern France (Prévost and Robert, 2016). Generally, urban planning documents do not explicitly consider urban soils as a means to 78 79 minimize run-off. In the case of France, local spatial planning documents - Plan Local d'Urbanisme (PLU), Schéma de cohérence territoriale (SCOT) - and flood 80

risk prevention strategies - Stratégie Locale de Gestion de Risques d'Inondation
(SLGRI), Plan de Prévention des Risques d'Inondation (PPRI) - do not yet consider
that the hydraulic properties of urban soils may influence stormwater infiltration.

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85 Stormwater infiltration relies generally on the characteristics of (1) soil and (2) ground surface. The major parameters are: (1) soil texture, structure, humidity, 86 87 depth, soil organic carbon (SOC), compaction and existence of impervious layers (Elrick et al., 1989; Gregory et al., 2006; Mayor et al., 2009); and (2) slope, vegetal 88 cover type and density, presence of rock fragments, artifacts, cracks, biological 89 activity or crusts on the ground surface (Mayor et al., 2009; Mavimbela and van 90 Rensburg, 2017; Morbidelli et al., 2018). Urban areas have a mosaic of relict natural 91 92 soils and other soils, strongly impacted by anthrosolization (human activities). The removal of topsoil, backfilling with fine and coarse materials, earthworks and 93 94 ploughing lead to Anthrosols (AT) and Technosols (TC). According to the IUSS 95 Working Group WRB (2015), AT are soils generated by intensive agricultural land-96 use and backfilling with fine materials, while TC contain coarse materials produced by humans (artefacts and technical material). Anthrosolization thus generates 97 98 different hydrological properties in contrast to natural soils (Séré et al., 2012).

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The presence of coarse materials in the soil matrix of TC diminishes the area available for infiltration (Yilmaz et al., 2018). In addition, compaction in AT and TC limits infiltration since it reduces the bulk density and macroporosity (Gregory et al., 2006; Shuster et al., 2014). The impact of compaction in these soils is greater than in natural soils because they already present a limited porosity (Grabosky et al., 105 2009). Furthermore, the backfill materials used may induce specific processes such
106 as precipitation of carbonates that can narrow the pore size (Wissmeier and Barry,
107 2009; Yilmaz et al., 2013) and subsequently the water storage, exposing vegetation
108 to water stress (Urban, 2013; Huot et al., 2015).

109

Although the nature and composition of AT and TC can limit infiltration, some of them can significantly reduce run-off (Xiao and McPherson, 2011). Coarse materials can create fissures at the interface with fine backfill materials (Cousin et al., 2003; Wang et al., 2018). Similarly, vegetation cover and organic matter can enhance porosity (Layman et al., 2016; Wiesner et al., 2016).

115

116 The study of hydraulic properties on AT and TC can be done with infiltration techniques originally developed for natural soils. This is the case for methods based 117 118 on the Beerkan estimation of soil transfer parameters (BEST), which were used to 119 calculate hydraulic properties accurately on TC (e.g. the field-saturated soil hydraulic conductivity (K_{fs}), the soil water retention curve or the saturated hydraulic 120 121 curve) (Yilmaz et al., 2019). Nevertheless, BEST methods require the 122 determination of the bulk density, the soil water content prior to the experiment and 123 the particle size distribution (Lassabatere et al., 2006; Yilmaz et al., 2019). The 124 numerous requisites of the BEST methods made difficult to study hydraulic properties in every field condition. So, simplified approaches were developed to 125 estimate some hydraulic properties that were mainly limited to K_{fs}. Some examples 126 127 of simplified approaches are the One-Ponded Height Technique (Elrick et al., 1989), the Simplified Beerkan Infiltration test (SBI) (Bagarello et al., 2014) or the Wu1 and 128

Wu2 methods (Wu et al., 1999; Xu et al., 2012), which have not been applied to AT
or TC soils so far. On natural vegetated soils of different textures, Wu1 had similar
K_{fs} results to BEST_slope (Lassabatere et al., 2006) and Wu2 to BEST_intercept
(Yilmaz et al., 2010), but both Wu methods permitted to calculate K_{fs} in more soils
independently of the texture (Xu et al., 2012).

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135 In general, the contribution of AT and TC to stormwater infiltration and thus to the 136 mitigation of run-off in urban areas has not been fully assessed yet (Grabosky et al., 2009; Fletcher et al., 2013): the type of soil is often not detailed, preventing 137 comparison and/or generalization of the results, and Mediterranean urban areas, 138 prone to intense episodes of precipitation, have been little studied. Moreover, the 139 140 impact of the land-use history needs to be clarified, even if some studies showed 141 more infiltration on urban soils with older age of land-use (Yang and Zhang, 2011; 142 Shuster et al., 2014).

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For these reasons, the objectives of this study were (1) to assess the potential of vegetated urban soils to mitigate run-off in an area prone to intense episodes of precipitation via infiltration studies, (2) to identify the soil parameters that affect infiltration, and (3) to assess the influence of the land-use history on infiltration and, more specifically, the industrial history (tile industry). Field measurements and sampling were performed in Marseilles (France), in plots covering a large range of known current and past land-uses.

153 2.1. Study area

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Marseilles (France) is a coastal city of the Mediterranean Sea, with a little more 155 than 860,000 inhabitants (Insee, 2019). Marseilles is a landmark for the French 156 157 economy due to its port and industrial activities (Prévost and Robert, 2016). The dominant bedrocks are sandstones, conglomerates, marls and clays. The climate is a 158 hot-summer Mediterranean climate (Csa). The annual average precipitation is 515 159 mm. Rainfall is in autumn-winter after a dry-hot summer (Fig. 1 Supplementary 160 material). The rainiest months are September (77 mm) and October (67 mm) 161 (METEO-FRANCE, 2019a). Rainfall is variable with strong episodes of 162 precipitation in one day, with maxima from 92 to 193 mm in the period 1973-2018 163 (METEO-FRANCE, 2019b). Monthly average temperature ranges from 7.1°C in 164 165 January to 24.8°C in July.

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The study area (Fig. 1) is in the "urban" zone of the 16th district, as defined and 167 delimited in the urban planning document, Plan Local d'Urbanisme (PLU) (MAMP, 168 2017). The 16th district marks the northern city limit, with a transition towards the 169 170 surrounding natural areas. The urban fabric is strongly influenced by the commercial 171 harbour and the associated industrial and logistical zones (Robert, 2016). The "urban" zone extends over 7.2 km² and includes 1.0 km² of semi-natural and green zones, 2.9 172 km² of economic zones, 1.1 km² of transportation infrastructure, and 2.1 km² of low 173 density residential areas (data drawn from the "Occupation des sols à grande échelle 174 2011 – Côte Bleue" Database, developed and presented in Robert, 2016). This zone is 175

176 currently undergoing a process of urban renewal that jeopardizes unsealed soils (Robert, 2016). A particularity of the study area is that it has an industrial past 177 178 dominated by the tile industry. A sampling strategy was therefore designed to allow 179 for comparison between the area impacted by this industry (located in a clay basin) 180 and the rest of the "urban" area, which is assumed not to be impacted by this activity. The area impacted by the tile industry covers circa 16.7 % of the "urban" zone, a 181 percentage drawn from photointerpretation of the 1957 aerial image (IGN, 1957). It 182 183 includes former clay quarries for extraction, and tile factories. This area underwent intense earthworks and was backfilled with construction debris (bricks, tiles, gravel). 184

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186 2.2. Spatial data base construction

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188 A geographical database comprising aerial images, topographic maps, digital 189 elevation models, geological data, land use maps, roads and railways, buildings, 190 land planning zones and other data relevant to the study was organised into a GIS, 191 using ArcGIS (Fig. 2, Step A). The period covered by the data spans from the 1930s 192 to the middle of the 2010s. We first identified vegetated urban soils with the photointerpretation of the 2011 aerial images, the most recent images at the 193 194 beginning of the study (Fig. 2, Step B). Then, relying on aerial images and 195 topographic maps, we characterized the land-use history of those vegetated urban 196 soils in past decades via: (1) the search for potential intense earthworks activities 197 (Fig. 2 Step C), and (2) the age assessment of the land-use type observed in 2011 198 (Fig. 2, Step D).

Authorization was obtained to sample vegetated urban soils from June 2017 to June 2018: (1) 14 plots lying on former clay quarries and tile factories (T); (2) 13 plots not lying on former clay quarries or tile factories (NT); (3) one control plot in the surrounding shrubland not subjected to urbanization (Fig. 1). Given the sampling restrictions on urban soils, we performed one-shot sampling in the representative area of each plot.

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In the field, we categorized soil surfaces according to the vegetation cover as trees only, herbaceous & trees, herbaceous only, and herbaceous & shrub. Then we described soil profiles from auger cores or pit observations where possible. In the description, we noted soil depth, and described and sampled the first horizon (average thickness of 0.13 m).

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215 2.4. Penetration resistance measurement

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In addition to the sampling, we measured *in situ* the penetration resistance (Q_d) 217 218 and infiltration. Q_d gives information on soil compaction (Gregory et al., 2006; Keller et al., 2012; Bean and Dukes, 2015). Qd was measured with a constant weight 219 light dynamic cone penetrometer (Type 2, Sols Mesures, France), and the analysis 220 221 was stopped if 3 equal readings were taken or if the penetrometer reached the profile 222 depth. Then, we calculated Qd for the first 0.15 m of the soil profile since the highest 223 compaction occurs in the first 0.15 m (Yang and Zhang, 2011; Bean and Dukes, 224 2015). To check this, Q_d was also calculated for the surface horizon and for the depth profile. When there were several horizons within the 0.15 cm, Q_d was
weighted according to the thickness of these horizons.

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- 228 2.5. Infiltration experiment
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Between June 2017 and June 2018, we carried out a constant-head infiltration 230 231 experiment, following the Wu2 method (Wu et al., 1999; Xu et al., 2012). Given 232 the restrictions on operating in urban soils, infiltration was measured once in the field, and the experiment was repeated in 11 plots to check the measurement 233 (Supplementary Table 1). In the plots where the infiltration was repeated, the first 234 235 result was used. The Wu2 method was conducted using a single cylinder with a 236 shaped rim and an internal radius of 0.05 m. Before starting the experiment, the 237 vegetation was cut. Then, the cylinder was driven around 0.05 m into the soil, recording the exact cylinder depth and preserving the surface to avoid lateral flow. 238 239 Water was poured onto the soil inside the cylinder until a water head of 0.10 m. 240 From this moment on, the time started to be measured. When the water head reached 0.09 m, water was added until reaching 0.10 m again, and the added volume 241 and the time were recorded. This process was repeated for 2 to 3 hours until a steady 242 243 state was reached. At the end of the experiment, the volumes were plotted as a 244 function of time to obtain infiltration curves in order to identify the steady 245 infiltration of water, which was called infiltration rate. At this step, we discarded one plot out of 29 because of infinite infiltration. The cumulative height of 246 247 infiltrated water was also plotted with time to produce the curve required by the Wu2 method. 248

The Wu2 method assumes soil got saturated during the infiltration experiment. According to this assumption, the cumulative infiltration curve has an initial transient part and a final steady part. Those are determined since the former has a variable slope, while the latter a constant slope. The field-saturated soil hydraulic conductivity (K_{fs}) is then estimated from (Eq.1):

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$$K_{fs} = rac{i}{a f}$$

Equation 1. Equation to estimate the field-saturated soil hydraulic conductivity (K_{fs})
equation according to the Wu2 method (Xu et al., 2012).

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where *i* is the slope of the steady part of the cumulative infiltration curve, *a* an adimensional parameter equal to 0.9084 and *f* a correction factor. The *f* factor can be estimated from (Eq. 2):

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264

$$f = \frac{\left[H + \left(\frac{1}{\alpha}\right)\right]}{G^*} + 1$$

265 *Equation 2.* Correction factor (Wu et al., 1999).

266

267 where *H* is the water head, α a soil texture evaluation and *G** the adjustment 268 parameter of the infiltrometer characteristics. *G*^{*} can be determined by Eq. 3, where 269 *d* is the cylinder depth and *r* the radium of the cylinder:

270

$$G^* = d + \frac{r}{2}$$

- 272 Equation 3. Calculation of the adjustment parameter G* according to the
 273 characteristics of the ring infiltrometer (Wu et al., 1999).
- 274

Eq. 2 and 3 allow estimating K_{fs} in Eq. 1, but Eq.2 requires a field evaluation of the soil texture to choose α (*Wu et al., 1999*). The Wu parameter α takes 3 different values depending on the texture of the studied soil (Table 1). The texture class of the first horizon was assigned according to the particle-size distribution of the USDA triangle (Soil Science Division Staff, 2017). The selection of an erroneous α value does not compromise K_{fs} estimation (Bagarello et al., 2014). In fact, an improper choice produces an acceptable error (Elrick and Reynolds, 1992).

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284 2.6. Estimation of levels of run-off production

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Spatial planning requires an assessment of run-off production in urban soils to 286 287 manage the risk of run-off floods. The levels of run-off production can be estimated 288 through the combination of soil depth and K_{fs} to assist in the management of run-off flood risk in urban areas. Soil depth is related to the potential stormwater storage 289 while K_{fs} indicates the stormwater infiltration. We assessed the level of run-off 290 291 production based on an adaptation of the Hydrologic Soil Groups (HSG) (USDA-292 NCRS, 2009) (Table 2). Our criteria were: (1) soils have an estimated low run-off when $K_{fs} > 10 \ \mu m \ s^{-1}$ and soil depth $\ge 0.50 \ m$ (HSG A and B); (2) soils have an 293 estimated high run-off when $K_{fs} \leq 10 \ \mu m \ s^{-1}$ (HSG C and D), or when depth is < 294 0.50 m down to the impervious layer or to a very dense material (e.g. technogenic 295 296 material, bedrock) (HSG D). We did not quantify run-off production since our objective was to assess the infiltration of vegetated urban soils to mitigate run-off.
Furthermore, we did not test the influence of slope since most of the urbanized area
and the sampled plots were flat or on terraces.

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1 2.7. Physico-chemical analyses

The soil samples (first horizon) were dried at 40°C and sieved at 2 mm and further ground when needed. Samples were analyzed for soil organic carbon (SOC) (AFNOR, 1995a), total nitrogen (N) and Olsen phosphorus (P) (AFNOR, 1995b, 1995c), and particle-size distribution (AFNOR, 2003), as these factors may influence the infiltration experiment (Elrick et al., 1989; Gregory et al., 2006; Mayor et al., 2009).

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309 2.8. Soil data statistical treatment

310 The statistical analyses of soil data were performed in R (R Core Team, 2017). Prior to the significance test, normality was checked using the Shapiro test, QQ 311 312 plots and density plots. K_{fs}, Q_d and infiltration rate had a non-normal distribution. We investigated the significance of mean differences in (1) infiltration rate, K_{fs}, Q_d 313 314 and soil depth to assess the studied soils, and (2) K_{fs} to study the influence of the age 315 of the current land-use and the vegetation cover on K_{fs}. Owing to the non-normal 316 distribution of the parameters, non-parametric multivariate statistics were used, namely the Kruskal-Wallis test and a post-hoc Dunn's test with the packages FSA, 317 318 car and rcompanion (Mangiafico, 2017; Ogle, 2017; Fox and Weisberg, 2011). The parameters affecting K_{fs} were explored with the Pearson test using the packages 319 320 Hmisc and Corrplot (Harrell Jr and Dupont, 2018; Wei and Simko, 2017).

322 3. Results

323 324

3.1. Urban soil characteristics

The studied urban soils were predominantly Technosols, followed by Anthrosols (Table 2 Supplementary material). The coarse materials were composed of construction debris, gravel for all soils and additional brick fragments in T soils. The only natural soil was a Regosol (C) (IUSS Working Group WRB, 2015) found in the surrounding shrubland. Another Regosol was found in one NT plot, in a private garden, where it was considered as a relict soil.

331 Soils were thicker in urbanized areas than in the C area (Fig. 3). A majority of 332 soils had a depth exceeding 0.50 m. Although the difference was not significant, 333 NT soils were deeper than T soils.

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3.1.1. SOC, N and P contents

Anthrosols and Technosols had a high content of soil organic carbon (SOC), total nitrogen (N) and available phosphorus (P). Although the T soils had less SOC, N and P than NT soils, the variability of these parameters was too high (Table 3) to detect any significant difference between the two groups. In general NT soils had more organic matter and T soils had less SOC and N than the C Regosol. Moreover, the NT Regosol contained twenty times more P, 1.7 times more SOC and 1.4 times more N than the C Regosol.

3.1.2. Mechanical properties

347 The mechanical properties of urban soils may be relevant for the infiltration of 348 stormwater and hence for the run-off production of soils. The particle-size distribution of the groups of studied soils varied slightly, but non-significantly (Fig. 349 350 4). T soils had more clay and silt than NT and C soils while NT and C soils had the same clay content, and NT contained less silt than the C one. Nevertheless, most of 351 352 soils had a loam soil texture in the first horizon (Table 2 Supplementary material). Q_d for the first 0.15 m was > 2 MPa for most of the studied soils, including 100 % 353 354 of the T soils, and was significantly higher in T than in NT soils (Fig. 3).

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357

356 3.2. Levels of run-off production of urban soils

358 The studied Anthrosols and Technosols were able to infiltrate stormwater. The 359 infiltration was similar in the NT and T plots, but lower than in the C plot (Fig. 3). The infiltration curves showed that T and NT soils experienced a strong variability 360 (Fig. 5). The infiltration experiment allowed for the estimation of the field-saturated 361 362 hydraulic conductivity (K_{fs}). The K_{fs} relates to the infiltration of urban soils that can be estimated when the curve of the cumulative infiltration reaches a steady state. At 363 364 saturation, it is possible to apply the Wu2 linear equations to estimate K_{fs} (Fig. 6). 365 The K_{fs} coupled with the soil depth enabled the estimation of the levels of run-off production on urban soils to be estimated. Our results highlighted that some 366 vegetated Anthrosols and Technosols could mitigate run-off. We found that 14.3 % 367 368 of T and 84.6 % of NT soils had an estimated low run-off production (Table 3). The estimated run-off production was not modified when the infiltration experiment was 369

replicated (Table 3 Supplementary material). Since the run-off production relied both on the K_{fs} and the soil depth, the latter being constant for a given plot, the only parameter that could modify the estimation of run-off production in alternate infiltration experiments was K_{fs} .

The results of K_{fs} were similar to the results of infiltration rates, showing that T 374 and NT soils had lower K_{fs} than C (Fig. 3). In addition, the geometric mean of K_{fs} 375 in T was two times lower than in NT soils (Table 3). Furthermore, K_{fs} was not 376 correlated to Q_d, the particle-size distribution, or to P content in both T and NT 377 soils (Table 4). There was a trend between Kfs and SOC and N in both types of 378 379 soils, although not significant. K_{fs} was only significantly correlated to N in T soils 380 (r = 0.55 and p-value = 0.039). However, N was significantly correlated to SOC in T (r = 0.97 and p-value < 0.001) and NT soils (r=0.92 and p-value < 0.001). Also, 381 382 the geometric mean of SOC and N was lower in T soils (Table 3).

383

384 On the other hand, there was a significant difference in K_{fs} between soils with a 385 current < 13-year-old and > 13-year-old land-use (Fig. 7). The lowest K_{fs} was in 386 soils with a < 13-year-old land-use, which also corresponded to T soils. There was 387 no significant difference in K_{fs} with respect to the type of existing vegetation cover, 388 however (Fig.8).

389

390 4. Discussion

391 4.1. Urban soil characteristics

The studied soils were mainly Technosols, with only some Anthrosols, 393 regardless of whether they lay on former clay quarries, tile factories (T) or not (NT). 394 The historical presence of the tile industry induced a lower organic matter content in 395 396 T soils than in NT soils, probably because the formers were younger, with a current vegetated land-use of less than 13 years. In the literature a lower organic matter 397 content was found to be associated to the presence of brick in the coarse materials, 398 which was also the case in the T soils. Technosols containing brick in both fine 399 earth and skeleton had 1.8 % SOC and 1.4 g N kg⁻¹ (Nehls et al., 2013) and 2.1 % 400 SOC and 1.2 g N kg⁻¹ (Schleuß et al., 1998), while Anthrosols and Technosols 401 without brick in the coarse material had 4.7 \pm 3.5 % SOC and 2.4 \pm 2.7g N kg⁻¹ 402 (Schleuß et al., 1998), and 4.7 \pm 3.7 % SOC and 3.3 \pm 1.9g N kg⁻¹ (Lorenz and 403 Kandeler, 2005). These studies also revealed a huge variability in SOC and N 404 405 contents. The variability was also high in our results but T and NT soils had more 406 SOC than the cited studies.

407

One characteristic of urban soils is their depth. Soil depth controls the volume 408 of stormwater that a soil can infiltrate. Urbanization processes, such as pavement 409 410 construction, can remove surficial horizons of urban soils making them shallower than other soils (Kida and Kawahigashi, 2015). However, most of the studied 411 412 Anthrosols and Technosols had the required depth to store enough stormwater and avoid run-off. In our study, one of the soils which did not satisfy this requirement 413 was the C (control) Regosol. The reason was that this soil was on a slope, unlike 414 415 the N and NT soils, and had probably experienced erosion in the past, like most Mediterranean soils. In other studies, Anthrosols and Technosols were twice as 416 deep and were never shallower than 0.50 m (Schleuß et al., 1998; Lorenz and 417

Kandeler, 2005). The soil depth of urban soils should therefore be locally assessed
to estimate the run-off production in a given urban area and cannot be estimated
from the depth of natural soils.

421

422 Given the impact of human activities on urban soils, the penetration resistance 423 for the first 0.15 m (Q_d) is a critical characteristic of these soils and a proxy of soil 424 compaction (Gregory et al., 2006; Keller et al., 2012; Bean and Dukes, 2015). The 425 Q_d for most of the studied Anthrosols and Technosols was > 2 MPa, including the totality of T soils and the C Regosol. This threshold indicates that the soils were 426 427 compacted, limiting root growth (Materechera et al., 1992; Soil Science Division Staff, 2017). The C Regosol was also found to be compacted because it had 428 429 numerous rock fragments originating from the bedrock. The compaction of T soils highlighted the strong impact of the earthworks associated to the demolition of tile 430 431 factories and the backfilling of clay quarries.

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4.2.

Vegetated urban soils mitigate run-off

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The infiltration of vegetated urban soils is usually not evaluated because of their supposed lower infiltration in contrast to natural soils. The decrease in infiltration was demonstrated in a study which intentionally compacted vegetated natural soils with construction machines (Gregory et al., 2006). Similarly, in our results K_{fs} was lower in Anthrosols and Technosols than in the C Regosol. Unfortunately, it is often considered that all urban soils have the same properties and a limited infiltration. Consequently, this aspect is not taken into consideration in

spatial planning. However, our results highlighted that vegetated Anthrosols and 442 Technosols can infiltrate enough stormwater to limit run-off. The methodology 443 considered that soils generate run-off when the infiltration and the storage capacity 444 445 are overwhelmed by the amount of stormwater. Both parameters, Kfs and soil depth were respectively estimated and measured for each plot. On the contrary, other 446 studies have simulated run-off production based on K_{fs} only. For example, Shuster 447 et al. (2014) simulated the run-off production of Technosols that had experienced 448 449 demolition. They reported that soils with low field-unsaturated hydraulic conductivity (K_{fun}) produced as much as twenty times the run-off of soils with high 450 K_{fun} (75,000 l y⁻¹ versus 1130 to 3800 l y⁻¹). The simulations of Yang and Zhang 451 (2011), which employed several intensities of rainfall, also found that Anthrosols 452 and Technosols with a reduced infiltration produced more run-off. None of these 453 454 studies considered the soil depth in the simulation of run-off. In our results, 66.7 % of Anthrosols and Technosols had an elevated K_{fs} (> 10 μ m s⁻¹) according to Soil 455 456 Science Division Staff (2017) but only 48.1 % of these soils had low run-off (Table 457 3). In addition, the proportion of soils with low run-off in T soils was five times less than in NT soils. For this reason, the parameters that influence the run-off 458 459 production need to be investigated more in detail.

460

461

462

4.3. Soil parameters affecting field-saturated hydraulic conductivity

463 Run-off production depends mainly on two independent factors, the soil depth 464 and K_{fs} . The relevance of soil depth is that it is associated to the reservoir of 465 stormwater that Anthrosols and Technosols can store, as previously discussed. K_{fs} 466 presented a large range of values in both T and NT soils, showing that the

infiltration experiment employed was useful to discriminate urban soils. K_{fs} 467 468 variation is produced by several factors. K_{fs} may be sensitive to the materials contained in Technosols. The K_{fs} geometric mean of T soils was four times as high 469 470 as that of Technosols constructed with a mixture of paper sludge (Séré et al., 2012) and two times that of Technosols composed of waste from the iron industry (Huot 471 et al., 2015). In other cases, such as in Technosols containing rubble, K_{fs} was highly 472 variable, ranging from 5.6 to 66.7 μ m s⁻¹) (Scalenghe and Ferraris, 2009; Shuster et 473 al., 2014; Yilmaz et al., 2018). 474

475 The method employed to measure K_{fs} also influences the value. In Yilmaz et 476 al. (2019), Beerkan estimation of soil transfer parameters (BEST) and the method with multiple tension disc infiltration, applied to a constructed Technosol composed 477 of rubble and green waste, gave respectively K_{fs} values of 8.8 and 26.3 μ m s⁻¹. 478 Furthermore, seasonality may influence K_{fs}, which appeared to be reduced when 479 the soil was more humid (Wiesner et al., 2016). Nevertheless, we did not observe 480 481 such variation between the different campaigns because the soil was always dry 482 according to the soil profile description.

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As seen previously, compaction is a characteristic of urban soils. Compaction tends 484 to decrease stormwater infiltration in Anthrosols and Technosols. Compaction can 485 486 influence the mechanical properties of urban soils, increasing the bulk density. The higher the bulk density, the shorter the macropores and the smaller the pore size 487 (Gregory et al., 2006; Yang and Zhang, 2011). Although most of the Anthrosols 488 and Technosols that we studied were compacted, some of them had elevated K_{fs} 489 values and a low run-off production and Q_d was not significantly correlated to K_{fs}. 490 Olson et al. (2013) found a lack of correlation between K_{fs}, compaction and bulk 491

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density in Technosols with a construction past. Considering our results, compaction 492 493 may not be a general proxy of K_{fs} in urban soils. We did not study porosity, but the macropore density could be responsible for the elevated K_{fs} values. In a study of 494 495 agricultural soils, K_{fs} was correlated to elongated transmission pores (50-500 µm) and fissures (> 500 µm) (Pagliai et al., 2004). Provided compaction reduces 496 elongated transmission pores in agricultural soils (Alaoui et al., 2018; Pagliai et al., 497 498 2004), fissures may enhance K_{fs} in compacted urban soils. The presence of coarse 499 material in Technosols (e.g. gravel) could create fissures at the interface with the 500 fine material (Cousin et al., 2003; Yilmaz et al., 2018), especially during shrinking 501 and swelling in clay-rich soils such as the T soils. In addition, the porosity could be 502 provided by porous coarse materials such as brick fragments (Nehls et al., 2013). 503 This aspect will require in-depth study in the future.

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505 We also found that the organic matter content was only linked to K_{fs} in recent 506 vegetated Anthrosols and Technosols. Kfs was significantly correlated to the N 507 content in recent vegetated soils (<13 years), although N and SOC compose the organic matter and were significantly correlated in all soils. Recent vegetated soils 508 509 (<13 years) had significantly lower K_{fs} and had less SOC and N. Accordingly, organic matter may be a discriminating parameter at the beginning of soil 510 511 development only. At this stage, it enhances vegetation installation, root proliferation (De Lucia et al., 2013; Layman et al., 2016) and the formation of 512 513 aggregates. These parameters increase the macropore density (Vidal-Beaudet and 514 Charpentier, 1998; Chen et al., 2014). In our case, the effect may disappear when Anthrosols and Technosols are rich in organic matter (SOC > 3.4 % and N > 2.4 g 515 kg⁻¹) and their current land-use is older than 13 years. SOC and N values above a 516

threshold of 3.4 % and 2.4 g kg⁻¹ respectively may not induce further positive effect on K_{fs} , but it is observed that amendments increase K_{fs} in most of cases (Kranz et al., 2020).

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4.4. Impact of land-use history on infiltration in urban soils

The land-use history affects the K_{fs} of Anthrosols and Technosols, and thus the 523 524 run-off production. According to our results, K_{fs} was low in recent urban soils with a current vegetated land-use < 13-year-old. The influence of the historical 525 526 background could be due to several factors, such as the intensity of earthworks, the structure evolution of Technosols, the way in which construction debris was 527 deposited and soil was managed. In our set of soils, the low K_{fs} corresponded to 528 529 Anthrosols and Technosols that had experienced intense earthworks during 530 dismantling of the tile factory and quarries. Similarly, Shuster et al. (2014) found, 531 in Technosols subjected to demolition, that < 14-15-year-old soils had a lower 532 infiltration than > 14-15-year-old soils, since recent Technosols had been affected by more intense earthworks. 533

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The structure of vegetated urban soils may evolve with the age of the current landuse. The structure of one-year-old constructed Technosols and Anthrosols can be dominated by gravity and compaction and, is more influenced by roots and soil organisms from 2-4 years on (Jangorzo et al., 2013; Bouzouidja et al., 2018). Seré et al. (2012) tested a constructed Technosol in lysimeters for 3 years. They observed an early process of pedogenesis, which created sub-horizons and

improved the structure by the formation of micro and macro-aggregates. Scalenghe 541 and Ferraris (2009) studied three Technosols on a slope embankment of 0, 4 and 40 542 543 years. They also observed the formation of horizons and described in detail the 544 evolution of porosity in a Technosol. The initial total porosity was reduced after 4 years, but it was twice as high as the porosity after 40 years (70 % v/v). Such an 545 increase in porosity increased the initial K_{fs} from 11.7 to 66.7 µm s⁻¹. Thus, the 546 evolution of porosity may explain why Anthrosols and Technosols with an older 547 548 land-use history have larger K_{fs}. Lastly, the way coarse materials are incorporated into the soil or deposited at the surface, the lack of ploughing or amendments may 549 reduce K_{fs} (Yang and Zhang, 2011). Therefore, the assessment of the infiltration on 550 vegetated urban soils requires a detailed study of the historical background. 551

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4.5. The type of vegetation cover is not relevant for run-off estimation

555 The type of vegetation cover might modify stormwater infiltration in 556 Anthrosols and Technosols. We hypothesized that soils presenting a mixture of trees, shrubs and herbaceous plants would have high K_{fs} values, as found in (Wang 557 558 et al., 2018). Although it was easy to establish categories of vegetation cover, it 559 proved to be difficult to identify them in the field because the vegetation cover was 560 heterogeneous and often had several configurations and densities for the same plot. As a result, the type of vegetation was not a determining factor for the stormwater 561 562 infiltration, as it was also found by Yang and Zhang (2011). In addition, the type of 563 vegetation cover does not have a significant role in run-off regulation in natural 564 Mediterranean soils, because bare soils are the main generators of run-off (Mayor et 565 al., 2009).

566 In order to better understand how to mitigate the risk of run-off flood in urban 567 areas, it would be necessary to study K_{fs} on bare Anthrosols and Technosols to check the data against natural soils. Bare urban soils may likely produce significant 568 569 run-off in areas subjected to episodes of heavy precipitation. To prevent run-off, the vegetation cover should be maintained in these areas. However, spatial planning 570 should adapt the management to the properties of Technosols because the low 571 572 available water content can expose plants to hydric stress (Huot et al., 2015; Urban, 573 2013).

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4.6. Conclusion

Our results showed that vegetated urban soils can infiltrate enough stormwater 577 to mitigate run-off in urban areas with episodes of heavy precipitation, such as 578 Marseilles (France). The estimation of potential levels of run-off production in 579 580 Anthrosols and Technosols based on the soil depth and the field-saturated hydraulic 581 conductivity (K_{fs}) enabled soils to be discriminated according to their land-use history. Organic matter appeared to have a positive effect on K_{fs} in the early stage of 582 583 T soils formation and hence on reducing their potential run-off. Urban soils are a key asset to mitigate the risk of run-off flood in urban areas, but are usually 584 neglected in planning documents, while we show that they may have a low level of 585 run-off production via a large K_{fs} (> 10 μ m s⁻¹) and a significant depth (> 0.5 m). 586 Therefore, a sound planning approach to mitigate run-off should consider 587 588 Anthrosols and Technosols, along with other strategies (e.g. stormwater basins). This implies characterizing these soils for their physico-chemical and physical 589 590 properties, including their infiltration, but also assessing their land-use history. In 591doing so, it would contribute to the new European strategy to minimize run-off in592areas prone to extreme episodes of precipitation (European Commission, 2015).593Although quantifying the run-off was beyond the scope of this paper, the594minimization of soil sealing appears to be a sustainable strategy to mitigate run-off.595Further research is needed, however, to refine the estimate of field-saturated soil596hydraulic conductivity (K_{fs}) in Anthrosols and Technosols of urban areas, since the597method used to measure K_{fs} can affect the estimation of the run-off.

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601

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849 6. Tables

850

851 Table 1 Suggested values for α^* according to soil structure (Wu et al., 1999).

852

α* [cm⁻¹]	Comments			
0.36	Sand			
0.12	Loam			
0.04	Clay			

853

854 Table 2 Levels of run-off production based on Hydrologic Soil Groups

855 (HSG) (USDA-NCRS, 2009). Field-saturated soil hydraulic conductivity (Kfs),

and soil depth.

857

Category	Equivalence to HSG	K _{fs} (µm s⁻¹)	Soil Depth (m)	
Low run-off	A and B	K _{fs} > 10	≥ 0.50	
High run-off	C and D	$K_{fs} \leq 10$	≥ 0.50	
High run-off	D	-	< 0.50	

858

859

Table 3 Urban soils characteristics. Descriptive statistics for the first horizon of Soil Organic Carbon content (SOC), Total Kjeldahl nitrogen (N), and Olsen phosphorus (P); Descriptive statistics of the infiltration rate (Infiltration), field-saturated hydraulic conductivity (K_{fs}), and total depth of the soil profile (Depth); soils with estimated low run-off production (Low run-off); for (T) plots that lay on former clay quarries, tile factories; for (NT) plots that did not lie on former clay quarries or tile factories (NT), and (C) shrubland used as control soil.

	SOC	Ν	Р	Infiltration	K _{fs}	Depth	Low run-off
	(%)	(g kg ⁻¹)	(g kg ⁻¹)	(mm h⁻¹)	(µm s⁻¹)	(m)	(%)
T (n=14)							84.6
Geometric Mean ± SD	2.7 ± 2.8	2.0 ± 1.8	0.05 ± 0.08	117.6 ± 546.7	12.3 ± 51.0	0.59 ± 0.28	
Median	3	2.2	0.06	54.1	6.0	0.68	
Min	0.2	0.3	0.01	14.4	1.5	0.20	
Max	10.8	7.3	0.29	1705.3	154.7	1.00	
NT (m. 42)							14.3
NT (n=13)							
Geometric Mean ± SD	5.4 ± 1.6	3.0 ± 1.4	0.33 ± 0.19	301.3 ± 190.2	26.7 ± 16.0	0.71 ± 0.23	
Median	5.3	2.8	0.29	333.3	29.5	0.70	
Min	3.4	2.0	0.14	71.7	7.3	0.45	
Max	9.2	7.0	0.80	707.1	57.5	1.10	
C (n=1)							
Value	3.9	2.5	0.01	2334.9	150.1	0.40	

867	Table 4: Pearson Correlation values between Field-saturated soil hydraulic
868	conductivity (K $_{\rm fs})$ and Soil Organic Carbon (SOC), Total Kjeldahl N (N), Olsen
869	P (P), clay content (Clay), silt content (Silt), sand content (Sand), and
870	Penetration resistance in the first 0.15 m (Q_d). The Pearson correlation (r) values
871	are shown for: (1) plots that lay on former clay quarries, tile factories (T), and
872	(2) plots that did not lie on former clay quarries or tile factories (NT). Pearson
873	coefficients statistically significant (P-values < 0.050) are noted as *. Observed
874	trends between variables which were not statistically significant ($0.051 < P$ -
875	value < 0.069) are noted as ¹ .

Kfs	SOC	Ν	Р	Clay	Silt	Sand	Q₀
T n=14	0.50 ¹	0.55*	-0.16	0.50 ¹	0.15	-0.37	-0.41
NT n=13	0.46	0.54 ¹	0.12	-0.21	-0.15	0.18	-0.35