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6 [Title](#)

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30

31 **Abstract**

32

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

55 [Keywords](#)

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

57

58 1. Introduction

59

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

71

72 One of the goals of planning documents is to tackle flood risks in order to reduce
73 both hazards and vulnerability. Water management strategies encourage the
74 collection of stormwater to alleviate the hazard, either by adapting the sewer
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,
78 urban planning documents do not explicitly consider urban soils as a means to
79 minimize run-off. In the case of France, local spatial planning documents - Plan
80 Local d'Urbanisme (PLU), Schéma de cohérence territoriale (SCOT) - and flood

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

84

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

99

100 The presence of coarse materials in the soil matrix of TC diminishes the area
101 available for infiltration (Yilmaz et al., 2018). In addition, compaction in AT and
102 TC limits infiltration since it reduces the bulk density and macroporosity (Gregory
103 et al., 2006; Shuster et al., 2014). The impact of compaction in these soils is greater
104 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

110 Although the nature and composition of AT and TC can limit infiltration, some of
111 them can significantly reduce run-off (Xiao and McPherson, 2011). Coarse
112 materials can create fissures at the interface with fine backfill materials (Cousin et
113 al., 2003; Wang et al., 2018). Similarly, vegetation cover and organic matter can
114 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
117 techniques originally developed for natural soils. This is the case for methods based
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
120 hydraulic conductivity (K_{fs}), the soil water retention curve or the saturated hydraulic
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
125 properties in every field condition. So, simplified approaches were developed to
126 estimate some hydraulic properties that were mainly limited to K_{fs} . Some examples
127 of simplified approaches are the One-Ponded Height Technique (Elrick et al., 1989),
128 the Simplified Beerkan Infiltration test (SBI) (Bagarello et al., 2014) or the Wu1 and

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

134

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.,
137 2009; Fletcher et al., 2013): the type of soil is often not detailed, preventing
138 comparison and/or generalization of the results, and Mediterranean urban areas,
139 prone to intense episodes of precipitation, have been little studied. Moreover, the
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).

143

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

151

152 2. Materials and methods

153 2.1. Study area

154

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

166

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

176 currently undergoing a process of urban renewal that jeopardizes unsealed soils
177 (Robert, 2016). A particularity of the study area is that it has an industrial past
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.
181 The area impacted by the tile industry covers circa 16.7 % of the “urban” zone, a
182 percentage drawn from photointerpretation of the 1957 aerial image (IGN, 1957). It
183 includes former clay quarries for extraction, and tile factories. This area underwent
184 intense earthworks and was backfilled with construction debris (bricks, tiles, gravel).

185

186 2.2. Spatial data base construction

187

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
193 photointerpretation of the 2011 aerial images, the most recent images at the
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).

199

2.3. Soil data acquisition

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.

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).

2.4. Penetration resistance measurement

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

225 depth profile. When there were several horizons within the 0.15 cm, Q_d was
226 weighted according to the thickness of these horizons.

227

228 2.5. Infiltration experiment

229

230 Between June 2017 and June 2018, we carried out a constant-head infiltration
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
233 field, and the experiment was repeated in 11 plots to check the measurement
234 (Supplementary Table 1). In the plots where the infiltration was repeated, the first
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,
238 recording the exact cylinder depth and preserving the surface to avoid lateral flow.
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
241 reached 0.09 m, water was added until reaching 0.10 m again, and the added volume
242 and the time were recorded. This process was repeated for 2 to 3 hours until a steady
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
246 one plot out of 29 because of infinite infiltration. The cumulative height of
247 infiltrated water was also plotted with time to produce the curve required by the
248 Wu2 method.

249

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

255

$$256 \quad K_{fs} = \frac{i}{a f}$$

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

259

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

263

$$264 \quad f = \frac{\left[H + \left(\frac{1}{\alpha} \right) \right]}{G^*} + 1$$

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 radius of the cylinder:

270

$$271 \quad G^* = d + \frac{r}{2}$$

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

274

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

282

283

284 2.6. Estimation of levels of run-off production

285

286 Spatial planning requires an assessment of run-off production in urban soils to
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
289 flood risk in urban areas. Soil depth is related to the potential stormwater storage
290 while K_{fs} indicates the stormwater infiltration. We assessed the level of run-off
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
293 when $K_{fs} > 10 \mu\text{m s}^{-1}$ and soil depth ≥ 0.50 m (HSG A and B); (2) soils have an
294 estimated high run-off when $K_{fs} \leq 10 \mu\text{m s}^{-1}$ (HSG C and D), or when depth is $<$
295 0.50 m down to the impervious layer or to a very dense material (e.g. technogenic
296 material, bedrock) (HSG D). We did not quantify run-off production since our

297 objective was to assess the infiltration of vegetated urban soils to mitigate run-off.
298 Furthermore, we did not test the influence of slope since most of the urbanized area
299 and the sampled plots were flat or on terraces.

300

301 2.7. Physico-chemical analyses

302 The soil samples (first horizon) were dried at 40°C and sieved at 2 mm and further
303 ground when needed. Samples were analyzed for soil organic carbon (SOC)
304 (AFNOR, 1995a), total nitrogen (N) and Olsen phosphorus (P) (AFNOR, 1995b,
305 1995c), and particle-size distribution (AFNOR, 2003), as these factors may
306 influence the infiltration experiment (Elrick et al., 1989; Gregory et al., 2006;
307 Mayor et al., 2009).

308

309 2.8. Soil data statistical treatment

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

321

322 3. Results

323 3.1. Urban soil characteristics

324

325 The studied urban soils were predominantly Technosols, followed by
326 Anthrosols (Table 2 Supplementary material). The coarse materials were composed
327 of construction debris, gravel for all soils and additional brick fragments in T soils.
328 The only natural soil was a Regosol (C) (IUSS Working Group WRB, 2015) found
329 in the surrounding shrubland. Another Regosol was found in one NT plot, in a
330 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.

334

335 3.1.1. SOC, N and P contents

336

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

344

3.1.2. Mechanical properties

The mechanical properties of urban soils may be relevant for the infiltration of 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. 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 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 % of the T soils, and was significantly higher in T than in NT soils (Fig. 3).

3.2. Levels of run-off production of urban soils

The studied Anthrosols and Technosols were able to infiltrate stormwater. The 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 (Fig. 5). The infiltration experiment allowed for the estimation of the field-saturated 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 saturation, it is possible to apply the Wu2 linear equations to estimate K_{fs} (Fig. 6). 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 vegetated Anthrosols and Technosols could mitigate run-off. We found that 14.3 % 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

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

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

392

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

407

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

418 Kandeler, 2005). The soil depth of urban soils should therefore be locally assessed
419 to estimate the run-off production in a given urban area and cannot be estimated
420 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
426 totality of T soils and the C Regosol. This threshold indicates that the soils were
427 compacted, limiting root growth (Materechera et al., 1992; Soil Science Division
428 Staff, 2017). The C Regosol was also found to be compacted because it had
429 numerous rock fragments originating from the bedrock. The compaction of T soils
430 highlighted the strong impact of the earthworks associated to the demolition of tile
431 factories and the backfilling of clay quarries.

432

433 4.2. Vegetated urban soils mitigate run-off 434

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

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

460

461 4.3. Soil parameters affecting field-saturated hydraulic conductivity

462

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

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

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
477 with multiple tension disc infiltration, applied to a constructed Technosol composed
478 of rubble and green waste, gave respectively K_{fs} values of 8.8 and 26.3 $\mu\text{m s}^{-1}$.
479 Furthermore, seasonality may influence K_{fs} , which appeared to be reduced when
480 the soil was more humid (Wiesner et al., 2016). Nevertheless, we did not observe
481 such variation between the different campaigns because the soil was always dry
482 according to the soil profile description.

483

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

492 density in Technosols with a construction past. Considering our results, compaction
493 may not be a general proxy of K_{fs} in urban soils. We did not study porosity, but the
494 macropore density could be responsible for the elevated K_{fs} values. In a study of
495 agricultural soils, K_{fs} was correlated to elongated transmission pores (50-500 μm)
496 and fissures ($> 500 \mu\text{m}$) (Pagliai et al., 2004). Provided compaction reduces
497 elongated transmission pores in agricultural soils (Alaoui et al., 2018; Pagliai et al.,
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.

504

505 We also found that the organic matter content was only linked to K_{fs} in recent
506 vegetated Anthrosols and Technosols. K_{fs} was significantly correlated to the N
507 content in recent vegetated soils (<13 years), although N and SOC compose the
508 organic matter and were significantly correlated in all soils. Recent vegetated soils
509 (<13 years) had significantly lower K_{fs} and had less SOC and N. Accordingly,
510 organic matter may be a discriminating parameter at the beginning of soil
511 development only. At this stage, it enhances vegetation installation, root
512 proliferation (De Lucia et al., 2013; Layman et al., 2016) and the formation of
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
515 Anthrosols and Technosols are rich in organic matter (SOC $> 3.4 \%$ and N $> 2.4 \text{ g}$
516 kg^{-1}) and their current land-use is older than 13 years. SOC and N values above a

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

520

521 4.4. Impact of land-use history on infiltration in urban soils

522

523 The land-use history affects the K_{fs} of Anthrosols and Technosols, and thus the
524 run-off production. According to our results, K_{fs} was low in recent urban soils with
525 a current vegetated land-use < 13-year-old. The influence of the historical
526 background could be due to several factors, such as the intensity of earthworks, the
527 structure evolution of Technosols, the way in which construction debris was
528 deposited and soil was managed. In our set of soils, the low K_{fs} corresponded to
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
533 by more intense earthworks.

534

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

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

552

553 4.5. The type of vegetation cover is not relevant for run-off estimation

554

555 The type of vegetation cover might modify stormwater infiltration in
556 Anthrosols and Technosols. We hypothesized that soils presenting a mixture of
557 trees, shrubs and herbaceous plants would have high K_{fs} values, as found in (Wang
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.
561 As a result, the type of vegetation was not a determining factor for the stormwater
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
568 check the data against natural soils. Bare urban soils may likely produce significant
569 run-off in areas subjected to episodes of heavy precipitation. To prevent run-off, the
570 vegetation cover should be maintained in these areas. However, spatial planning
571 should adapt the management to the properties of Technosols because the low
572 available water content can expose plants to hydric stress (Huot et al., 2015; Urban,
573 2013).

574

575 4.6. Conclusion

576

577 Our results showed that vegetated urban soils can infiltrate enough stormwater
578 to mitigate run-off in urban areas with episodes of heavy precipitation, such as
579 Marseilles (France). The estimation of potential levels of run-off production in
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
582 history. Organic matter appeared to have a positive effect on K_{fs} in the early stage of
583 T soils formation and hence on reducing their potential run-off. Urban soils are a
584 key asset to mitigate the risk of run-off flood in urban areas, but are usually
585 neglected in planning documents, while we show that they may have a low level of
586 run-off production via a large K_{fs} ($> 10 \mu\text{m s}^{-1}$) and a significant depth ($> 0.5 \text{ m}$).
587 Therefore, a sound planning approach to mitigate run-off should consider
588 Anthrosols and Technosols, along with other strategies (e.g. stormwater basins).
589 This implies characterizing these soils for their physico-chemical and physical
590 properties, including their infiltration, but also assessing their land-use history. In

591 doing so, it would contribute to the new European strategy to minimize run-off in
592 areas prone to extreme episodes of precipitation (European Commission, 2015).
593 Although quantifying the run-off was beyond the scope of this paper, the
594 minimization of soil sealing appears to be a sustainable strategy to mitigate run-off.
595 Further research is needed, however, to refine the estimate of field-saturated soil
596 hydraulic conductivity (K_{fs}) in Anthrosols and Technosols of urban areas, since the
597 method used to measure K_{fs} can affect the estimation of the run-off.

598

599

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621

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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 (K_{fs}),

856

and soil depth.

857

Category	Equivalence to HSG	K_{fs} ($\mu\text{m s}^{-1}$)	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

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861 **Table 3 Urban soils characteristics.** Descriptive statistics for the first horizon of Soil Organic Carbon content (SOC), Total Kjeldahl nitrogen
862 (N), and Olsen phosphorus (P); Descriptive statistics of the infiltration rate (Infiltration), field-saturated hydraulic conductivity (K_{fs}), and total
863 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
864 factories; for (NT) plots that did not lie on former clay quarries or tile factories (NT), and (C) shrubland used as control soil.

	SOC (%)	N (g kg⁻¹)	P (g kg⁻¹)	Infiltration (mm h⁻¹)	K_{fs} (μm s⁻¹)	Depth (m)	Low run-off (%)
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 (n=13)							14.3
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	

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867 **Table 4: Pearson Correlation values** between Field-saturated soil hydraulic
868 conductivity (K_{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.

876

Kfs	SOC	N	P	Clay	Silt	Sand	Q_d
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

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