

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

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ABSTRACT

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

1. Introduction

Extreme precipitation episodes may affect urban areas. The intensity of these episodes and poor infiltration in soils may generate run-off floods (Bhaduri et al., 2001; Chalvet and Claeys, 2011; Kundzewicz et al., 2014). These floods produce 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 Zhang, 2011). Several factors increase the risk of run-off flooding: (1) a higher intensity of precipitations (Trenberth, 2011) and (2) urbanization (Kundzewicz et al., 2014). Urbanization jeopardizes the territory, reducing permeable surfaces such as those found in French Mediterranean coastal zones (Robert et al., 2019). Urbanization also affects infiltration in soils since it contributes to compaction (Gregory et al., 2006; Yang and Zhang, 2011; Shuster et al., 2014).

One of the goals of planning documents is to tackle flood risks in order to reduce both hazards and vulnerability. Water management strategies encourage the collection of stormwater to alleviate the

hazard, either by adapting the sewer network or using sustainable drainage systems (Perales-Momparler et al., 2015). Spatial planning may also limit urbanization, but local planning practices can be 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 minimize run-off. In the case of France, local spatial planning documents – Plan Local d'Urbanisme (PLU), Schéma de cohérence territoriale (SCOT) – and flood 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.

Stormwater infiltration relies generally on the characteristics of (1) soil and (2) ground surface. The major parameters are: (1) soil texture, structure, humidity, 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 cover type and density, presence of rock fragments, artifacts, cracks, biological activity or crusts

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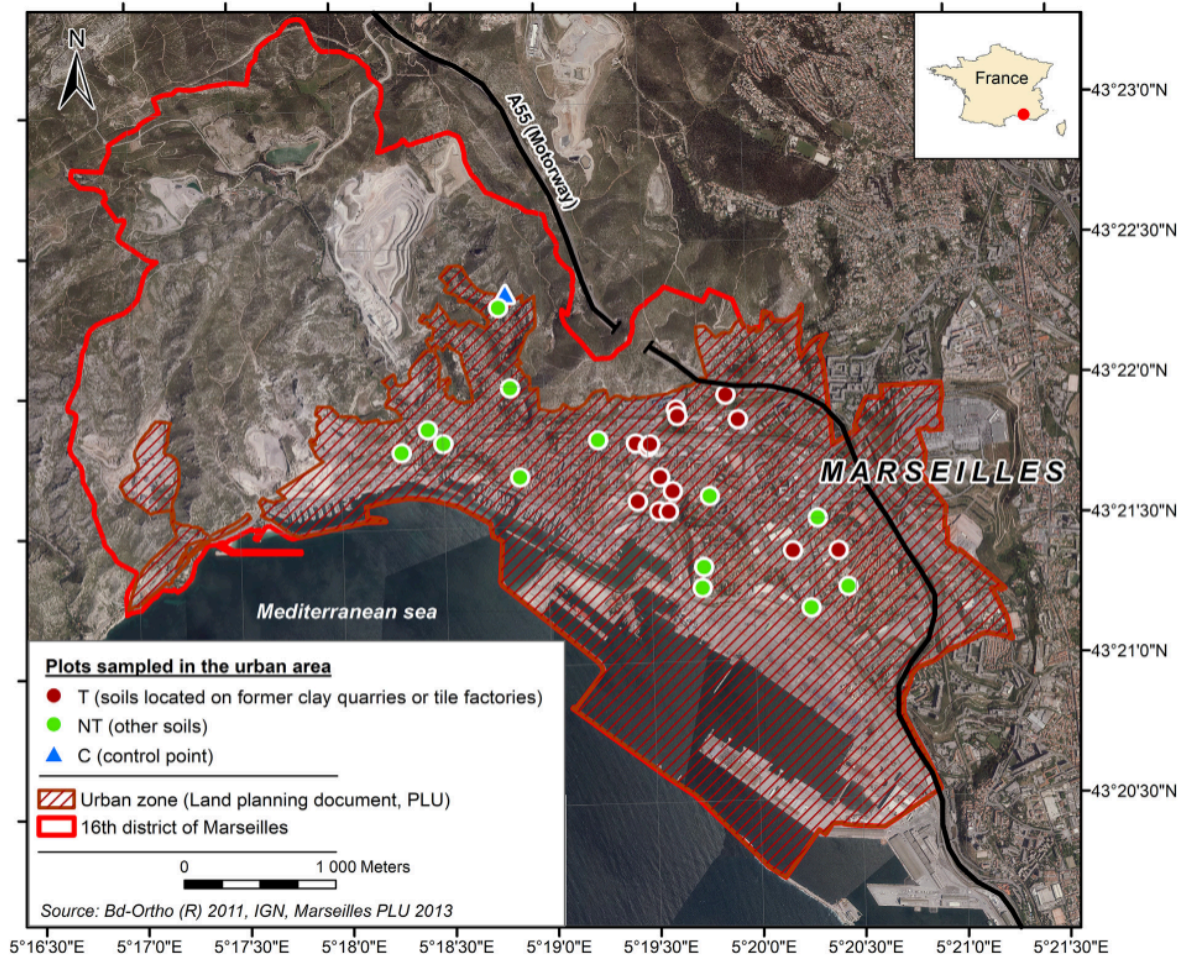


Fig. 1. Map of sampled plots. Location of the sampled plots in the 16th district of Marseilles on the 2011 orthophoto (IGN, 2011): plots in the “urban” zone that lay on former clay quarries, tile factories (T, $n = 14$), plots in the “urban” zone that did not lie on former clay quarries or tile factories (NT, $n = 13$), and the shrubland used as control soil (C, $n = 1$).

on the ground surface (Mayor et al., 2009; Mavimbela and van Rensburg, 2017; Morbidelli et al., 2018). Urban areas have a mosaic of relict natural soils and other soils, strongly impacted by anthrosolization (human activities). The removal of topsoil, backfilling with fine and coarse materials, earthworks and ploughing lead to Anthrosols (AT) and Technosols (TC). According to the IUSS Working Group WRB (2015), AT are soils generated by intensive agricultural land-use and backfilling with fine materials, while TC contain coarse materials produced by humans (artefacts and technical material). Anthrosolization thus generates different hydrological properties in contrast to natural soils (Séré et al., 2012).

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., 2009). Furthermore, the backfill materials used may induce specific processes such as precipitation of carbonates that can narrow the pore size (Wissmeier and Barry, 2009; Yilmaz et al., 2013) and subsequently the water storage, exposing vegetation to water stress (Urban, 2013; Huot et al., 2015).

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).

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 on the Beerkan estimation of soil transfer parameters (BEST), which were used to calculate hydraulic properties accurately on TC (e.g. the field-saturated soil hydraulic conductivity (K_s), the soil water retention curve or the saturated hydraulic curve) (Yilmaz et al., 2019). Nevertheless, BEST methods require the determination of the bulk density, the soil water content prior to the experiment and the particle size distribution (Lassabatere et al., 2006; Yilmaz et al., 2019). The numerous requisites of the BEST methods made difficult to study hydraulic properties in every field condition. So, simplified approaches were developed to estimate some hydraulic properties that were mainly limited to K_s . Some examples 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 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_s 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_s in more soils independently of the texture (Xu et al., 2012).

In general, the contribution of AT and TC to stormwater infiltration

and thus to the 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 comparison and/or generalization of the results, and Mediterranean urban areas, prone to intense episodes of precipitation, have been little studied. Moreover, the impact of the land-use history needs to be clarified, even if some studies showed more infiltration on urban soils with older age of land-use (Yang and Zhang, 2011; Shuster et al., 2014).

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.

2. Materials and methods

2.1. Study area

Marseilles (France) is a coastal city of the Mediterranean Sea, with a little more than 860,000 inhabitants (Insee, 2019). Marseilles is a landmark for the French 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 hot-summer Mediterranean climate (Csa). The annual average precipitation is 515 mm. Rainfall is in autumn-winter after a dry-hot summer (Fig. 1 Supplementary material). The rainiest months are September (77 mm) and October (67 mm) (METEO-FRANCE, 2019a). Rainfall is variable with strong episodes of precipitation in one day, with maxima from 92 to 193 mm in the period 1973–2018 (METEO-FRANCE, 2019b). Monthly average temperature ranges from 7.1 °C in January to 24.8 °C in July.

The study area (Fig. 1) is in the “urban” zone of the 16th district, as defined and delimited in the urban planning document, Plan Local d’Urbanisme (PLU) (MAMP, 2017). The 16th district marks the northern city limit, with a transition towards the surrounding natural areas. The urban fabric is strongly influenced by the commercial 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 km² of economic zones, 1.1 km² of transportation infrastructure, and 2.1 km² of low density residential areas (data drawn from the “Occupation des sols à grande échelle 2011 – Côte Bleue” Database, developed and presented in Robert, 2016). This zone is 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 dominated by the tile industry. A sampling strategy was therefore designed to allow for comparison between the area impacted by this industry (located in a clay basin) 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 percentage drawn from photointerpretation of the 1957 aerial image (IGN, 1957). It includes former clay quarries for extraction, and tile factories. This area underwent intense earthworks and was backfilled with construction debris (bricks, tiles, gravel).

2.2. Spatial data base construction

A geographical database comprising aerial images, topographic maps, digital elevation models, geological data, land use maps, roads and railways, buildings, land planning zones and other data relevant to the study was organised into a GIS, using ArcGIS (Fig. 2, Step A). The period covered by the data spans from the 1930s 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

beginning of the study (Fig. 2, Step B). Then, relying on aerial images and topographic maps, we characterized the land-use history of those vegetated urban soils in past decades via: (1) the search for potential intense earthworks activities (Fig. 2 Step C), and (2) the age assessment of the land-use type observed in 2011 (Fig. 2, Step D).

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

2.5. Infiltration experiment

Between June 2017 and June 2018, we carried out a constant-head infiltration experiment, following the Wu2 method (Wu et al., 1999; Xu et al., 2012). Given 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 (Supplementary Table 1). In the plots where the infiltration was repeated, the first result was used. The Wu2 method was conducted using a single cylinder with a shaped rim and an internal radius of 0.05 m. Before starting the experiment, the 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. Water was poured onto the soil inside the cylinder until a water head of 0.10 m. 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 and the time were recorded. This process was repeated for 2 to 3 h until a steady state was reached. At the end of the experiment, the volumes were plotted as a function of time to obtain infiltration curves in order to identify the steady 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 infiltrated water was also plotted with time to produce the curve required by the Wu2 method.

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):

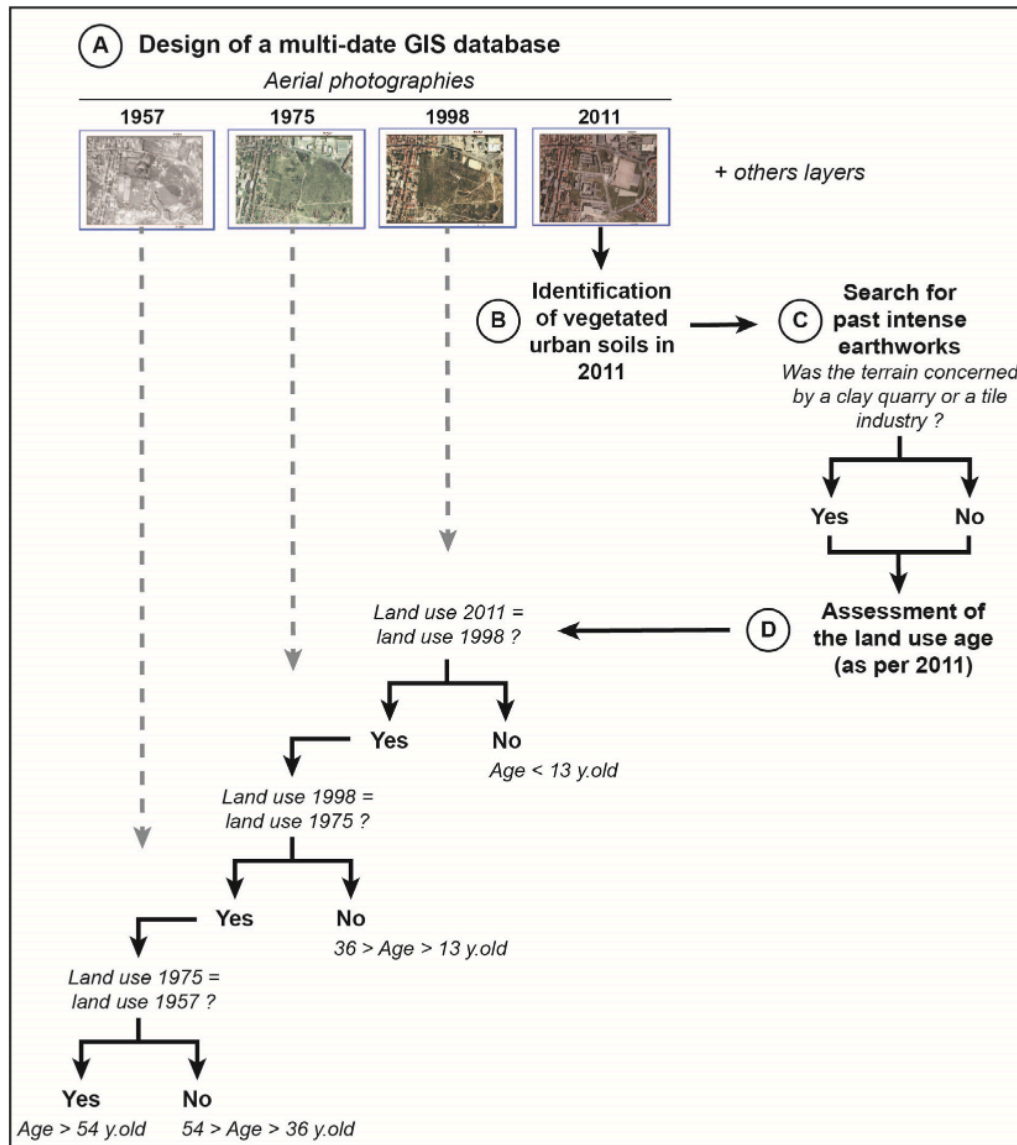


Fig. 2. Protocol to determine the historical background of vegetated urban soils.

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

α^* [cm^{-1}]	Comments
0.36	Sand
0.12	Loam
0.04	Clay

$$K_{fs} = \frac{i}{af} \quad (1)$$

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

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)):

$$f = \left[\frac{H + \left(\frac{1}{\alpha} \right)}{G^*} \right] + 1 \quad (2)$$

Correction factor (Wu et al., 1999). where H is the water head, α a soil texture evaluation and G^* the adjustment parameter of the infiltrometer characteristics. G^* can be determined by Eq. (3), where d is the cylinder depth and r the radius of the cylinder:

$$G^* = d + \frac{r}{2} \quad (3)$$

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

Eqs. (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).

Table 2

Levels of run-off production based on Hydrologic Soil Groups (HSG) (USDA-NCRS, 2009). Field-saturated soil hydraulic conductivity (K_{fs}), and soil depth.

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

2.6. Estimation of levels of run-off production

Spatial planning requires an assessment of run-off production in urban soils to manage the risk of run-off floods. The levels of run-off production can be estimated 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 while K_{fs} indicates the stormwater infiltration. We assessed the level of run-off production based on an adaptation of the Hydrologic Soil Groups (HSG) (USDA-NCRS, 2009) (Table 2). Our criteria were: (1) soils have an estimated low run-off when $K_{fs} > 10 \mu\text{m s}^{-1}$ and soil depth ≥ 0.50 m (HSG A and B); (2) soils have an estimated high run-off when $K_{fs} \leq 10 \mu\text{m s}^{-1}$ (HSG C and D), or when depth is < 0.50 m down to the impervious layer or to a very dense material (e.g. technogenic 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.

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,c), 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).

2.8. Soil data statistical treatment

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 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 and soil depth to assess the studied soils, and (2) K_{fs} to study the influence of the age of the current land-use and the vegetation cover on K_{fs} . Owing to the non-normal 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, 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 Hmisc and Corrplot (Harrell and Dupont, 2018; Wei and Simko, 2017).

3. Results

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, 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.

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

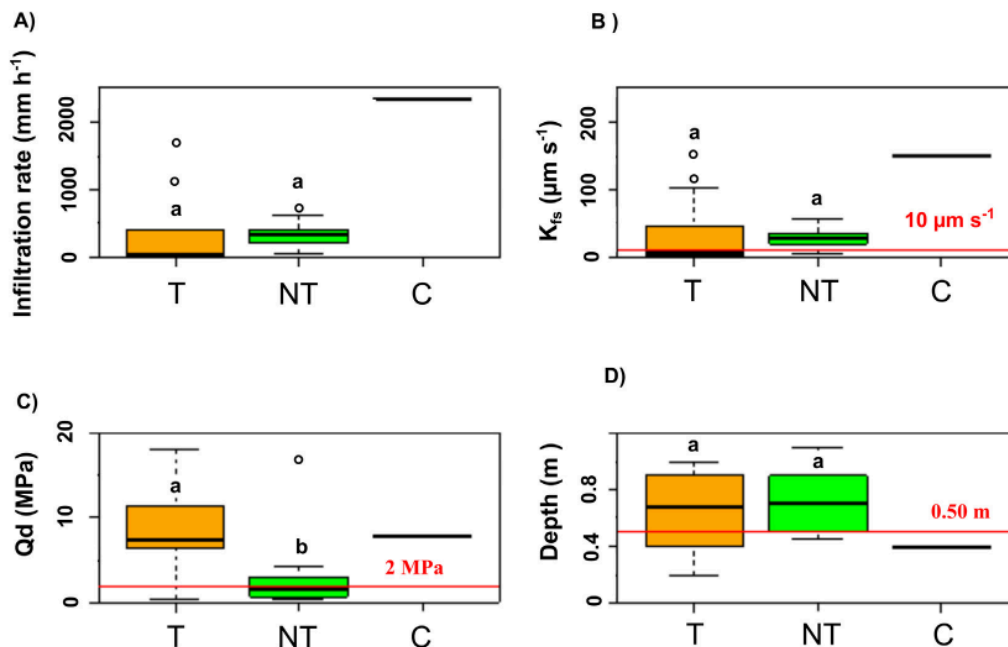


Fig. 3. Infiltration rate, field-saturated soil hydraulic conductivity (K_{fs}), penetration resistance (Q_d) and soil depth in vegetated urban soils. A) Infiltration rate on plots that lay on former clay quarries, tile factories (T, $n = 14$), plots that did not lie on former clay quarries or tile factories (NT, $n = 13$), and the shrubland used as control soil (C, $n = 1$). B) Field-saturated soil hydraulic conductivity (K_{fs}); the red line indicates high K_{fs} ($> 10 \mu\text{m s}^{-1}$), which we chose as a threshold to produce low run-off (Soil Science Division Staff, 2017; USDA-NCRS, 2009). C) Penetration resistance for the first 0.15 m (Q_d); the red line indicates the threshold for compaction ($> 2 \text{ MPa}$) (Soil Science Division Staff, 2017; Materechera et al., 1992). D) Soil depth; the red line indicates the threshold (0.50 m) we considered to estimate low run-off production (USDA-NCRS, 2009). Letters show significant differences between groups.

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 (%)	N (g kg^{-1})	P (g kg^{-1})	Infiltration (mm h^{-1})	K_{fs} ($\mu\text{m s}^{-1}$)	Depth (m)	Low run-off (%)
T (n = 14)							84.6
Geometric Mean $\pm$ SD	2.7 $\pm$ 2.8	2.0 $\pm$ 1.8	0.05 $\pm$ 0.08	117.6 $\pm$ 546.7	12.3 $\pm$ 51.0	0.59 $\pm$ 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 $\pm$ SD	5.4 $\pm$ 1.6	3.0 $\pm$ 1.4	0.33 $\pm$ 0.19	301.3 $\pm$ 190.2	26.7 $\pm$ 16.0	0.71 $\pm$ 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	

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

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

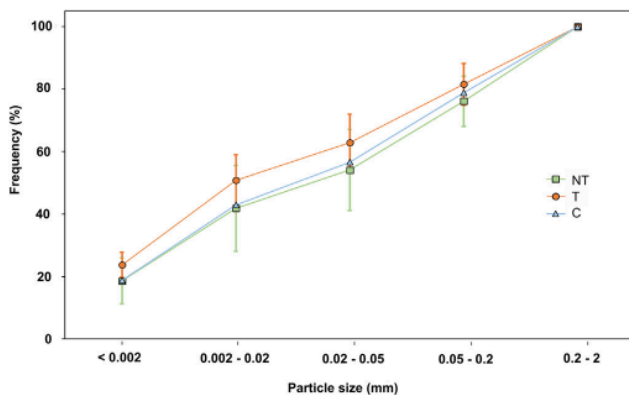


Fig. 4. Geometric mean particle size distribution on studied plots. Plots that lay on former clay quarries, tile factories (T, n = 14), plots that did not lie on former clay quarries or tile factories (NT, n = 13), and the shrubland used as control soil (C, n = 1).

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 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 and NT soils had lower K_{fs} than C (Fig. 3). In addition, the geometric mean of K_{fs} in T was two times lower than in NT soils (Table 3). Furthermore, K_{fs} was not correlated to Q_d , the particle-size distribution, or to P content in both T and NT soils (Table 4). There was a trend between K_{fs} and SOC and N in both types of soils, although not significant. K_{fs} was only significantly correlated to N in T soils ($r = 0.55$ 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, the geometric mean of SOC and N was lower in T soils (Table 3).

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

4. Discussion

4.1. Urban soil characteristics

The studied soils were mainly Technosols, with only some Anthrosols, regardless of whether they lay on former clay quarries, tile factories (T) or not (NT). The historical presence of the tile industry induced a lower organic matter content in 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 content was found to be associated to the presence of brick in the coarse materials, which was also the case in the T soils. Technosols containing

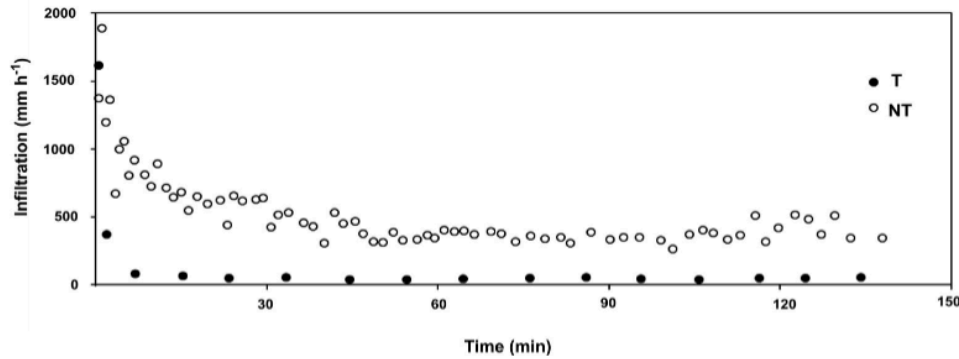


Fig. 5. Example of infiltration curves. Examples of one plot that lay on former clay quarries, tile factories (T), and one plots that did not lie on former clay quarries or tile factories (NT).

brick in both fine earth and skeleton had 1.8% SOC and 1.4 g N kg^{-1} (Nehls et al., 2013) and 2.1% SOC and 1.2 g N kg^{-1} (Schleuß et al., 1998), while Anthrosols and Technosols without brick in the coarse material had $4.7 \pm 3.5\%$ SOC and $2.4 \pm 2.7 \text{ g N kg}^{-1}$ (Schleuß et al., 1998), and $4.7 \pm 3.7\%$ SOC and $3.3 \pm 1.9 \text{ g N kg}^{-1}$ (Lorenz and Kandeler, 2005). These studies also revealed a huge variability in SOC and N contents. The variability was also high in our results but T and NT soils had more SOC than the cited studies.

One characteristic of urban soils is their depth. Soil depth controls the volume of stormwater that a soil can infiltrate. Urbanization processes, such as pavement construction, can remove surficial horizons of urban soils making them shallower than other soils (Kida and Kawahigashi, 2015). However, most of the studied 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 was the C (control) Regosol. The reason was that this soil was on a slope, unlike 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 deep and were never shallower than 0.50 m (Schleuß et al., 1998; Lorenz and 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.

Given the impact of human activities on urban soils, the penetration resistance for the first 0.15 m (Q_d) is a critical characteristic of these soils and a proxy of soil compaction (Gregory et al., 2006; Keller et al., 2012; Bean and Dukes, 2015). The Q_d for most of the studied Anthrosols and Technosols was $> 2 \text{ MPa}$, including the totality of T soils and the C Regosol. This threshold indicates that the soils were compacted, limiting root growth (Materechera et al., 1992; Soil Science Division f,

Table 4

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

K_{fs}	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

2017). The C Regosol was also found to be compacted because it had 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 factories and the backfilling of clay quarries.

4.2. Vegetated urban soils mitigate run-off

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

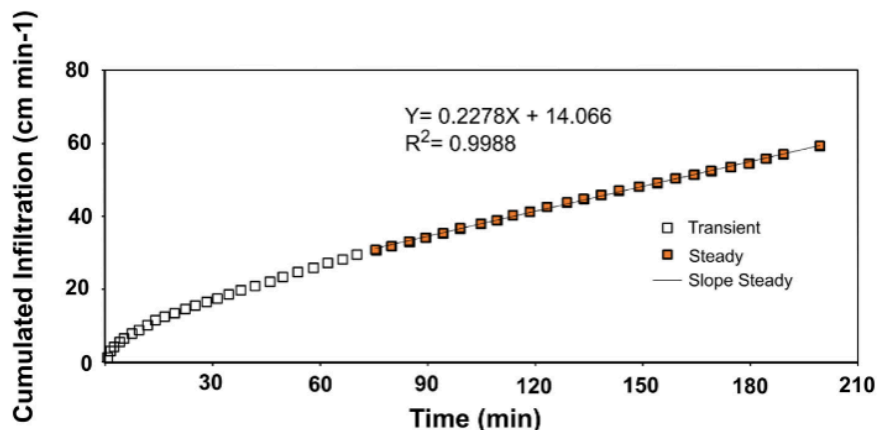


Fig. 6. Example of cumulated infiltration curve with time (t).

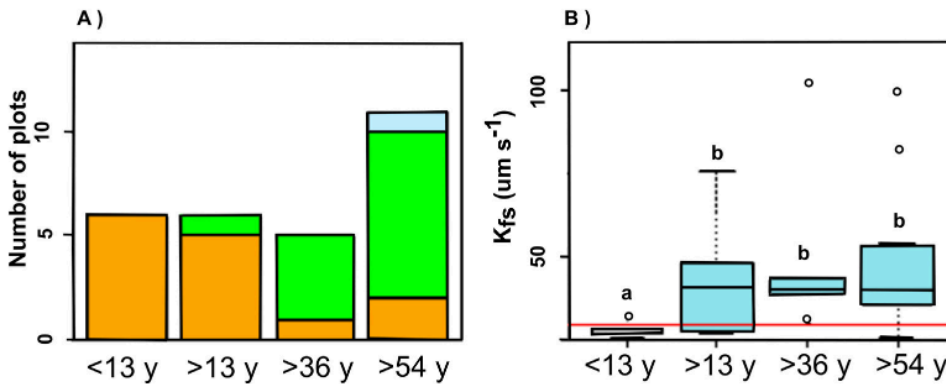


Fig. 7. Influence of the age of the 2011 land-use on field-saturated soil hydraulic conductivity. A) Age of the 2011 land-use: in years of the studied soils: < 13-year-old (< 13 y), > 13-year-old (> 13 y), > 36-year-old (> 36 y), and > 54-year-old (> 54 y). Plots that lay on former clay quarries, tile factories (T, n = 14), plots that did not lie on former clay quarries or tile factories (NT, n = 13), and the shrubland used as control soil (C, n = 1). B) Field-saturated soil hydraulic conductivity (K_{fs}) according to the age of the current land-use: < 13 years, > 13 > 36, and > 54 years. Letters show significant differences between groups.

limited infiltration. Consequently, this aspect is not taken into consideration in spatial planning. However, our results highlighted that vegetated Anthrosols and Technosols can infiltrate enough stormwater to limit run-off. The methodology considered that soils generate run-off when the infiltration and the storage capacity are overwhelmed by the amount of stormwater. Both parameters, K_{fs} and soil depth were respectively estimated and measured for each plot. On the contrary, other studies have simulated run-off production based on K_{fs} only. For example, Shuster et al. (2014) simulated the run-off production of Technosols that had experienced 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 K_{fun} (75,000 $l y^{-1}$ versus 1130 to 3800 $l y^{-1}$). The simulations of Yang and Zhang (2011), which employed several intensities of rainfall, also found that Anthrosols and Technosols with a reduced infiltration produced more run-off. None of these 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 $\mu m s^{-1}$) according to Soil Science Division Staff (2017) but only 48.1% of these soils had low run-off (Table 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 production need to be investigated more in detail.

4.3. Soil parameters affecting field-saturated hydraulic conductivity

Run-off production depends mainly on two independent factors, the soil depth and K_{fs} . The relevance of soil depth is that it is associated to the reservoir of stormwater that Anthrosols and Technosols can store, as previously discussed. K_{fs} 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} 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 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 et al., 2015). In other cases, such as in Technosols containing rubble, K_{fs} was highly variable, ranging from 5.6 to 66.7 $\mu m s^{-1}$ (Scalenghe and Ferraris, 2009; Shuster et al., 2014; Yilmaz et al., 2018).

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

As seen previously, compaction is a characteristic of urban soils. Compaction tends to decrease stormwater infiltration in Anthrosols and Technosols. Compaction can 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 (Gregory et al., 2006; Yang and Zhang, 2011). Although most of the Anthrosols and Technosols that we studied were compacted, some of them had elevated K_{fs} values and a low run-off production and Q_d was not significantly correlated to K_{fs} . Olson et al. (2013) found a lack of correlation between K_{fs} , compaction and bulk density in Technosols with a construction past. Considering our results, compaction 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

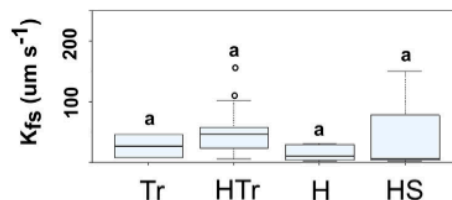


Fig. 8. Influence of vegetation cover type on field-saturated soil hydraulic conductivity. Field-saturated soil hydraulic conductivity (K_{fs}) according to vegetation cover type: trees only (Tr), herbaceous & trees (HTr), herbaceous only (H) and herbaceous & shrubs (HS). Letters show significant differences in groups.

agricultural soils, K_{fs} was correlated to elongated transmission pores (50–500 μm) and fissures ($> 500 \mu\text{m}$) (Pagliai et al., 2004). Provided compaction reduces elongated transmission pores in agricultural soils (Alaoui et al., 2018; Pagliai et al., 2004), fissures may enhance K_{fs} in compacted urban soils. The presence of coarse material in Technosols (e.g. gravel) could create fissures at the interface with the fine material (Cousin et al., 2003; Yilmaz et al., 2018), especially during shrinking and swelling in clay-rich soils such as the T soils. In addition, the porosity could be provided by porous coarse materials such as brick fragments (Nehls et al., 2013). This aspect will require in-depth study in the future.

We also found that the organic matter content was only linked to K_{fs} in recent vegetated Anthrosols and Technosols. K_{fs} was significantly correlated to the N 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 (< 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 development only. At this stage, it enhances vegetation installation, root proliferation (De Lucia et al., 2013; Layman et al., 2016) and the formation of aggregates. These parameters increase the macropore density (Vidal-Beaudet and 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 $> 2.4 \text{ g kg}^{-1}$) and their current land-use is older than 13 years. SOC and N values above a 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).

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 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 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 deposited and soil was managed. In our set of soils, the low K_{fs} corresponded to Anthrosols and Technosols that had experienced intense earthworks during dismantling of the tile factory and quarries. Similarly, Shuster et al. (2014) found, in Technosols subjected to demolition, that < 14 –15-year-old soils had a lower infiltration than > 14 –15-year-old soils, since recent Technosols had been affected by more intense earthworks.

The structure of vegetated urban soils may evolve with the age of the current land-use. 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 to 4 years on (Jangorzo et al., 2013; Bouzouidja et al., 2018). Séré 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 and Ferraris (2009) studied three Technosols on a slope embankment of 0, 4 and 40 years. They also observed the formation of horizons and described in detail the 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 increase in porosity increased the initial K_{fs} from 11.7 to 66.7 $\mu\text{m s}^{-1}$. Thus, the evolution of porosity may explain why Anthrosols and Technosols with an older 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 reduce K_{fs} (Yang and Zhang, 2011). Therefore, the assessment of the infiltration on vegetated urban soils requires a detailed study of the historical background.

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

The type of vegetation cover might modify stormwater infiltration in 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 et al. (2018). Although it was easy to establish categories of vegetation cover, it proved to be difficult to identify them in the field because the vegetation cover was 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 infiltration, as it was also found by Yang and Zhang (2011). In addition, the type of vegetation cover does not have a significant role in run-off regulation in natural Mediterranean soils, because bare soils are the main generators of run-off (Mayor et al., 2009).

In order to better understand how to mitigate the risk of run-off flood in urban 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 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 should adapt the management to the properties of Technosols because the low available water content can expose plants to hydric stress (Huot et al., 2015; Urban, 2013).

4.6. Conclusion

Our results showed that vegetated urban soils can infiltrate enough stormwater to mitigate run-off in urban areas with episodes of heavy precipitation, such as Marseilles (France). The estimation of potential levels of run-off production in Anthrosols and Technosols based on the soil depth and the field-saturated hydraulic 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 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 neglected in planning documents, while we show that they may have a low level of run-off production via a large K_{fs} ($> 10 \mu\text{m s}^{-1}$) and a significant depth ($> 0.5 \text{ m}$). Therefore, a sound planning approach to mitigate run-off should consider Anthrosols and Technosols, along with other strategies (e.g. stormwater basins). This implies characterizing these soils for their physico-chemical and physical properties, including their infiltration, but also assessing their land-use history. In doing so, it would contribute to the new European strategy to minimize run-off in areas prone to extreme episodes of precipitation (European Commission, 2015). Although quantifying the run-off was beyond the scope of this paper, the minimization of soil sealing appears to be a sustainable strategy to mitigate run-off. Further research is needed, however, to refine the estimate of field-saturated soil hydraulic conductivity (K_{fs}) in Anthrosols and Technosols of urban areas, since the method used to measure K_{fs} can affect the estimation of the run-off.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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