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Consequences of interactions between stormwater infiltration systems, shallow groundwater and underground structures at the neighborhood scale

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Abstract

This study investigates the interplay between stormwater infiltration devices, shallow groundwater and underground structures (sewer pipes and building foundations) at the neighborhood scale. Considering a hypothetical urban area, different scenarios are designed by varying the underground components taken into account within two soil types. For the least permeable soil, interactions with groundwater reduce the infiltration within devices (-99 to -151 mm/y) and increase the transpiration in surrounding areas (+42 to +50 mm/y). For both soils, the overall water table rise due to infiltration and mounding beneath infiltration devices increases groundwater drainage by sewer pipes and draining systems (+7 to +96 mm/y) and the water elevation differential between opposite walls of impervious structures (up to +1.5 m). In turn, underground structures strongly modify groundwater flow. For the least permeable soil, this directly affects groundwater influence on infiltration and transpiration and thus the overall effects of infiltration strategies at the neighborhood scale.

Keywords

Hydrological modeling; Urban hydrology; Hydrogeology; Stormwater infiltration; Water budget

1. Introduction

To mitigate urbanization impacts on surface and subsurface hydrology, stormwater management increasingly relies on small, decentralized infiltration systems. These systems are associated with various objectives, including the control of runoff and pollutant fluxes or the restoration of groundwater recharge. They are commonly classified as Sustainable Urban Drainage Systems (SUDS).

At the plot scale, a key concern is to correctly estimate the groundwater mounding beneath the SUDS which is likely to affect neighboring underground features (e.g. building foundations, sewer pipes) but also the functioning of the SUDS (Locatelli et al., 2015). The amplitude and dynamics of the mounding are controlled by the characteristics of the SUDS, the rain event, the hydrogeological context (Nimmer et al., 2009) and by surrounding conditions. The mounding may overlap with that of neighboring SUDS (Endreny & Collins, 2009) or be intercepted by sewer pipe trenches (Thompson et al., 2020). However, the influence of nearby underground structures (sewer pipes, foundations, drain) on the mounding magnitude and dynamics is poorly documented although they are likely to affect groundwater flows and levels (Attard et al., 2016a).

At the city scale, the low proportion of infiltrated volumes returned to the atmosphere by evapotranspiration and the presence of anthropogenic recharge sources (e.g. leakage from water supply networks, excessive irrigation) introduce a potential over-recharge of the aquifer that may result in a water table rise above predevelopment level (Göbel et al., 2004; Locatelli et al., 2017). The water table rise may increase groundwater seepages into sewer pipes (Kidmose et al., 2015; Rodriguez et al., 2020) and cause groundwater resurgences (Locatelli et al., 2017). These consequences are exacerbated in shallow water table environments. In such contexts, SUDS implementation therefore requires special attention (Zhang & Chui, 2019).

The evaluation of the hydrological impacts of stormwater infiltration is largely based on modeling. Hydrological models usually rely on simplified descriptions of actual composition and hydrological functioning of the subsurface compartment (Pophillat et al., 2021). For instance, the coupling between surface and subsurface hydrology is usually one-way, limiting the ability to account for subsurface feedbacks to the surface. Additionally, apart from a few studies that take into account groundwater seepages into sewer pipes (Kidmose et al., 2015), modeling approaches commonly neglects interactions between groundwater and underground structures. The literature provides only a partial understanding of the consequences of such hypotheses for the evaluation of stormwater infiltration strategies, especially in shallow groundwater environments.

The purpose of this paper 1) is to provide insights into the potential influence of interactions between surface hydrology, groundwater and underground structures on SUDS functioning and on their hydrological effects in shallow groundwater environment and 2) to discuss the implications for the modelling of urbanized areas with SUDS. The role of the various processes and interactions is investigated through the modeling of a hypothetical urban area for which different scenarios regarding the underground compartment are considered. The study area has a limited spatial extension (0.25 km^2), similar to that of an urban neighborhood or a small catchment. This extension, in the range identified by Golden et al. (2017) for evaluating the effect of LIDs and their interactions, is adapted to the scale of the phenomena studied. It allows considering multiple SUDS and the spatial variability of urban surface and underground features.

2. Materials and methods

2.1. Hypothetical urban area

The hypothetical area is shown in Figure 1. The domain has a 500 m x 500 m extension, a constant thickness of 10 m and a uniform slope of 1 %. Impervious areas (streets, parking, buildings) amount for 66 % of the area. The remaining 34% consist of green spaces and SUDS. The area is divided in 11 sub-basins for which all impervious surfaces and green spaces are connected to SUDS (10 swales (S1 to S10) and an infiltration basin (I1)). The latter are designed to manage the first 10 mm of runoff over their drainage area.

SUDS locations and associated drainage areas are shown in Figure 1. Depending on the scenario (section 2.2), different underground structures (sewer pipes, building foundations with or without drainage system) are included separately or cumulatively. Their location is shown in Figure 1 and their characteristics are described in section 2.2.

Soil properties are homogeneous throughout the domain. The groundwater level is imposed at the upstream and downstream boundaries (respectively left and right limits in Figure 1) at a depth of 3 m. The lateral boundaries (upper and lower boundaries in Figure 1) and the bedrock are impermeable. The overall groundwater flow is thus oriented along the main slope.

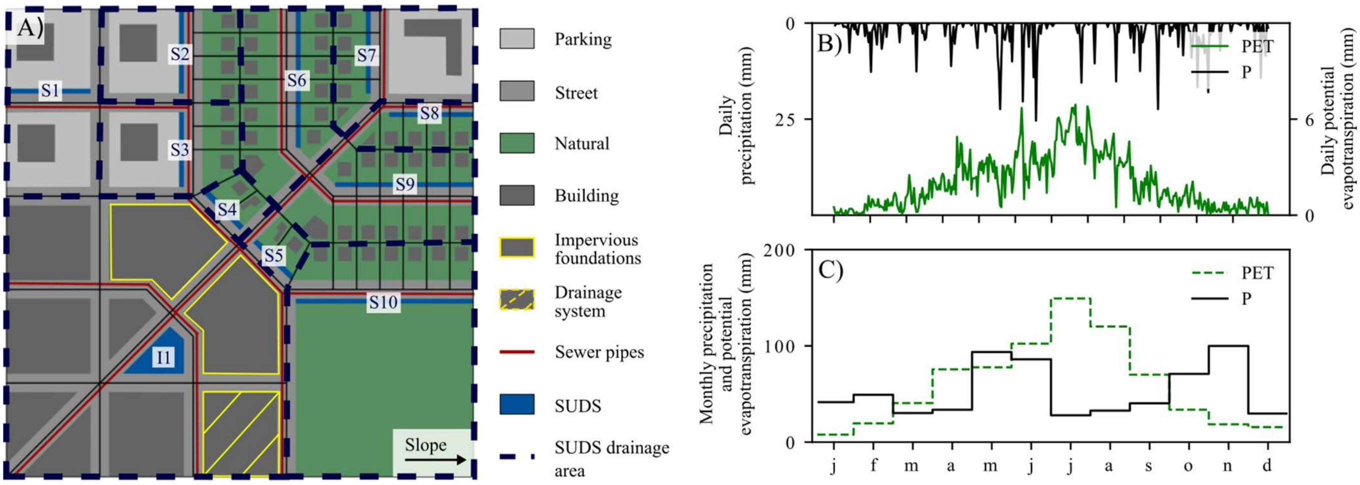

Figure 1: Description of the modeled case. Top view of the domain (A): spatial distribution of land use types, underground structures and SUDS (swales S1 to S10 and infiltration basin I1). Meteorological input used for the simulation aggregated to daily (B) and monthly (C) time steps.

The hydrological functioning of this environment is assessed over one year using rainfall (6 min) and PET (hourly, disaggregated from daily) records of year 2013 from the Trappes meteorological station (Paris Region, France, 48.77 °N - 2.01 °E) (Figure 1).

2.2. Scenarios

24 scenarios are designed, varying in soil types, underground configuration and SUDS implementation. Their main characteristics and the denominations used hereafter are described in Table 1.

Two soils are considered in order to highlight the hydrogeological context influence: a sandy loam (soil 1) and a sand (soil 2). Their characteristics are listed in Table 2. Six underground configurations are used to assess the influence of underground components. They are described in Table 1.

Simulations for the 2×6 scenarios regarding soil type and underground configuration are conducted with and without SUDS (e.g. 24 scenarios). The aim is to evaluate the influence of SUDS implementation on underground components. The description provided in 2.1 is adapted to simulate the catchment functioning with a conventional drainage system without SUDS: the runoff from the 11 sub-basins is directly conveyed to the sewer network and SUDS objects are simply replaced by green spaces (e.g. the impervious cover remains unchanged).

Pairwise comparisons of these scenarios are used to evaluate the influence of underground features (and associated interactions), with and without SUDS and under different soil conditions.

Table 1: Summary of modeling scenarios and corresponding denominations.

Underground configuration	**Objective**	**Conventional drainage system**		**Sustainable urban drainage system**	
		Sandy Loam	**Sand**	**Sandy Loam**	**Sand**
No water table nor underground structure (FD) - free drainage condition imposed at a depth of 3 m	Basis for assessing the influence of the water table	FD_{CONV} – Soil 1	FD_{CONV} – Soil 2	FD_{SUDS} – Soil 1	FD_{SUDS} – Soil 2
Water table without underground structure (GW)	Assessing the role of the water table Basis for assessing the role of underground structures	GW_{CONV} – Soil 1	GW_{CONV} – Soil 2	GW_{SUDS} – Soil 1	GW_{SUDS} – Soil 2
Water table with sewer pipes at a depth of 2 m (SP) - conductance of the pipe/trench system set at 10^{-6} ms^{-1} (pipe in relatively good condition (Karpf & Krebs, 2011)	Assessing the role of sewer pipes	SP_{CONV} – Soil 1	SP_{CONV} – Soil 2	SP_{SUDS} – Soil 1	SP_{SUDS} – Soil 2
Water table with impervious building foundations reaching a depth of 5 m (IF)	Assessing the role of impervious building foundation	IF_{CONV} – Soil 1	IF_{CONV} – Soil 2	IF_{SUDS} – Soil 1	IF_{SUDS} – Soil 2
Water table with a building equipped with a drainage system designed to lower the water table at the foundation bottom (DF)	Assessing the role of building foundations equipped with drainage systems	DF_{CONV} – Soil 1	DF_{CONV} – Soil 2	DF_{SUDS} – Soil 1	DF_{SUDS} – Soil 2
Water table with all underground structures described above (CE)	Assessing the cumulative influence of underground structures	CE_{CONV} – Soil 1	CE_{CONV} – Soil 2	CE_{SUDS} – Soil 1	CE_{SUDS} – Soil 2

Table 2: Brooks and Corey parameters for the two modeled soil types (Rawls et al., 1982)

Soil type	Saturated hydraulic conductivity (mm h^{-1})	Saturated water content (-)	Residual water content (-)	Shape parameter α (mm^{-1})	Shape parameter n (-)
Sandy loam	25.9	0.453	0.041	0.00682	0.322
Sand	210	0.437	0.02	0.0138	0.592

2.3. Modeling approach

The various scenarios are simulated using the URBS model (Rodriguez et al., 2008) which allows for continuous simulations of the hydrological functioning of urbanized watersheds. The calculation is based on a watershed discretization into urban hydrological elements (UHEs), each composed of a cadastral parcel and half of the associated street segment. For each UHE, flows and storage are computed at each time step by land use profile (natural, street, building and stormwater management structures) considering, among others, interception by vegetation, evaporation from surface storage and vegetation, infiltration, runoff, transpiration from soil storage and exchanges with groundwater (considering capillary upwelling from the water table). URBS can simulate runoff transfer through the urban drainage system considering different source control devices. Groundwater flows are modeled by a 2D application of Darcy's law on a subsurface mesh built by subdividing UHEs into triangle elements, considering drains and wells, groundwater seepage in sewer pipes and barrier effect generated by impermeable structures. For more details, readers may refer to Rodriguez et al. (2008) for the surface hydrology representation and to Pophillat et al. (2021) for the underground compartment representation.

The hypothetical area is discretized into 70 UHEs varying from 1 100 to 40 000 m² (Figure 1). The subsurface is discretized into 1238 triangular meshes (varying from 7 to 5821 m²) with a refinement in the vicinity of underground structures and SUDS. The soil is vertically discretized from the surface to the bedrock into ten reservoirs of 0.5 m thickness topping one reservoir of 5 m thickness.

Tree coverage is set at 20 % for street profiles and 50 % for natural and SUDS profiles. The interception reservoir capacity is set at 1 mm. The average depth of the root profile on vegetated areas is set at 50 cm. The storage capacity of the surface reservoirs is set at 0.5 mm for building, 1.5 mm for streets and 4 mm for natural areas (Rodriguez et al., 2008). The storage capacity of SUDS is calculated as the volume resulting from a 10 mm water depth over their drainage area. This value is one of the permanent rainfall retention targets for Paris region (DRIEE, 2020) and is thus consistent with the meteorological records used for the simulations

The simulations are carried out over a continuous period using a 6 min time step. An initialization of subsurface storage conditions is performed by repeating the one-year meteorological record described above (year 2013 from Trappes station) until a negligible variation (< 1 %) in infiltration, evapotranspiration, groundwater recharge and groundwater level is achieved between two consecutive repetitions. The analysis is then conducted over the last repetition, e.g., a one-year period with stable initial conditions.

3. Results

Figure 2 provides an overview of the results associated with the 24 scenarios. It allows comparing water balance and subsurface storage conditions depending on the underground component considered for simulations and soil types, with or without SUDS. A more detailed analysis of the differences between the scenarios is provided in subsequent sections and figures.

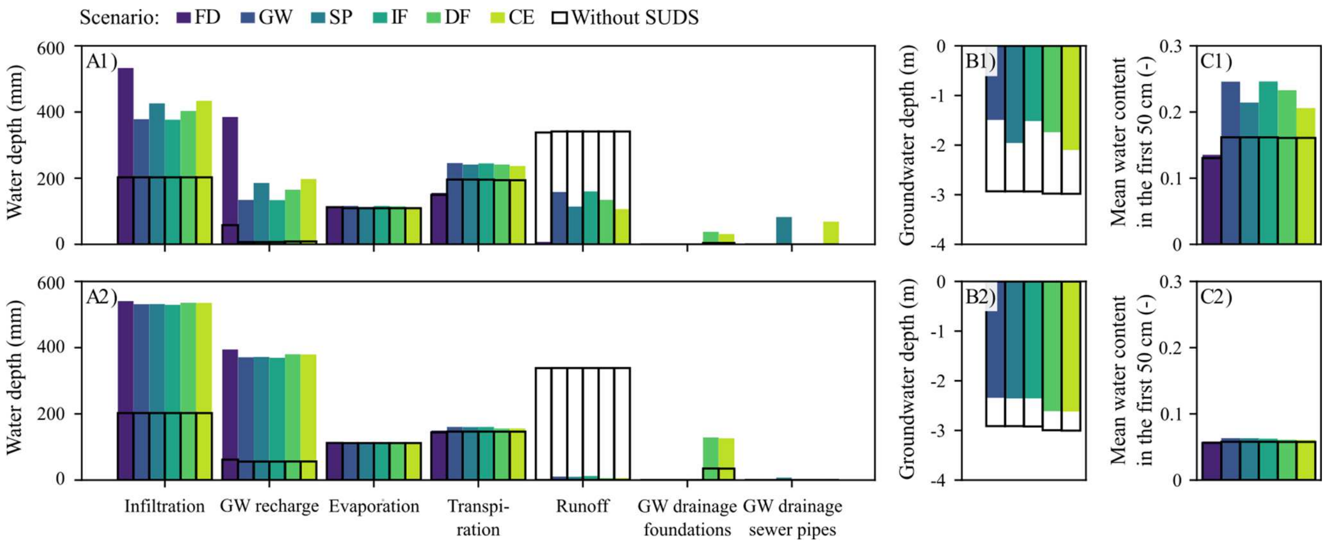

Figure 2: Overall simulation results for the sandy loam (1) and the sand (2). Components of the water budget (A), average groundwater depth (B) and average water content in the first 50 cm (C) over the whole domain and simulation time.

3.1. Results without underground structures

The role of interactions between volumes infiltrated within SUDS, water table and transpiration without underground structures is evaluated by comparing the scenario with SUDS and GW (GW_{SUDS}) with that (i) with SUDS but without interactions with GW (FD_{SUDS}), and (ii) with GW but without SUDS (GW_{CONV}).

3.1.1. SUDS effects on groundwater levels

SUDS significantly increase the groundwater recharge (Figure 2-A1 and A2) and, consequently, the average groundwater level (Figure 2-B1 and B2) for both soils. Although the recharge is higher for soil 2 (Figure 2-A), the higher aquifer transmissivity allows a faster lateral discharge of infiltrated volumes which results in a lower water table rise than for soil 1 (Figure 2-B1 and B2).

The water table rise is highly heterogeneous (Figure 3-C1 and C2). For soil 1, SUDS cause a widespread rise (Figure 3-C1). In the northern part of the domain, mounding beneath neighboring SUDS overlap and produce a large area where the average groundwater depth (GWD) is below 0.5 m (Figure 3-C1). The GWD also tends towards 0 in the infiltration basin indicating a quasi-permanent connection with the water table (Figure 3-C2). For soil 2, the high aquifer transmissivity limits water table fluctuations and only the infiltration basin causes a water table rise that affect mean groundwater levels (Figure 3-C2).

Stormwater infiltration also results in larger fluctuations of the mean groundwater level with both large seasonal variations, driven by rainfall seasonality, and faster variations in response to concentrated recharge in SUDS (Figure 3-A1 and A2).

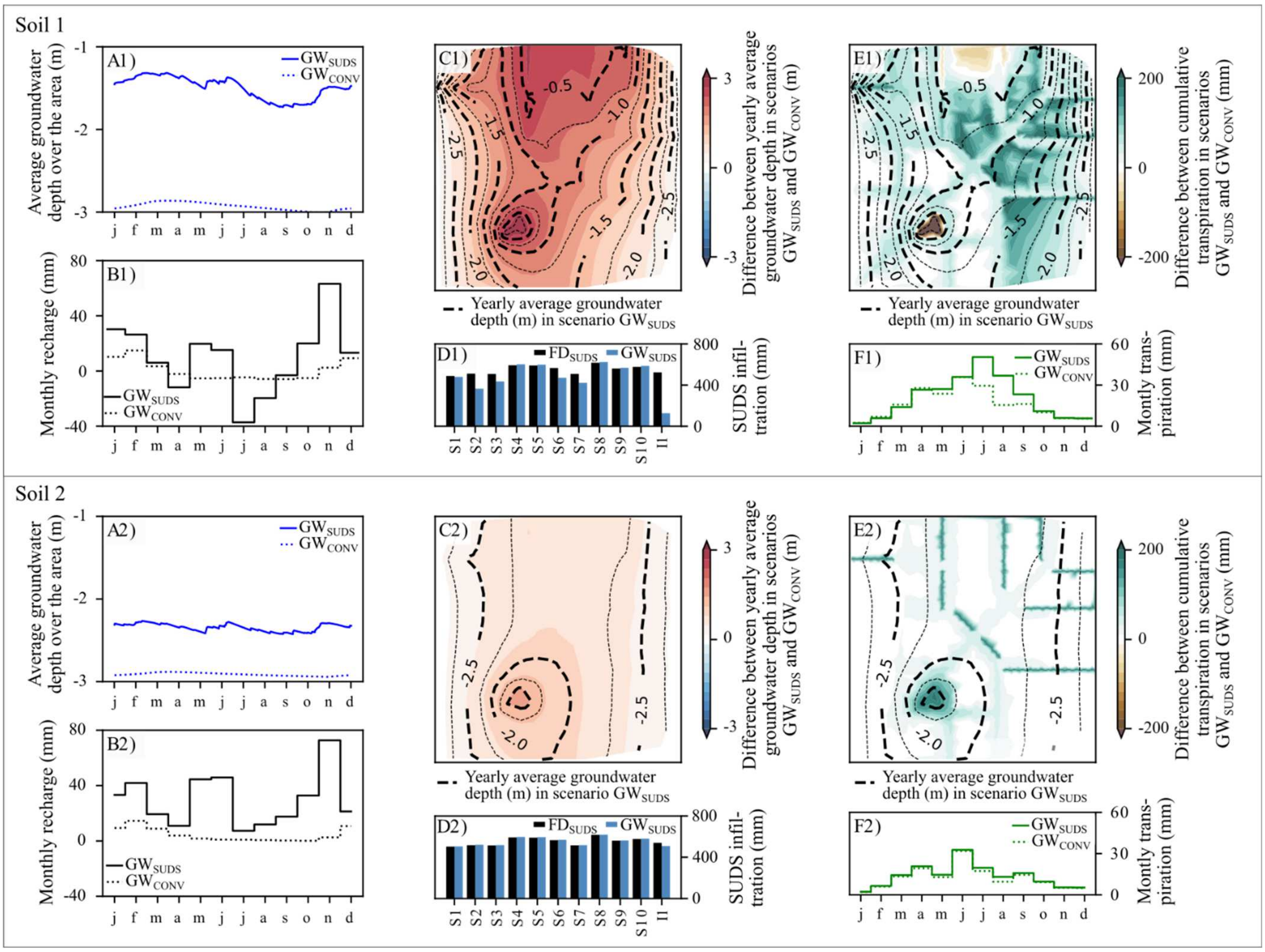

Figure 3: Simulation results for scenario GW_{SUDS} (without underground structure) for soil 1 (sandy loam) and 2 (sand). Comparison with scenario GW_{CONV} (corresponding scenario without SUDS) to assess the SUDS influence on average groundwater depth over the domain (A), on monthly groundwater recharge over the domain (B) on yearly average groundwater depth at each point of the domain (C), on cumulative transpiration at each point of the domain (E) and on monthly transpiration over the domain (F). Comparison with scenario FD_{SUDS} (no interactions with groundwater) to assess the groundwater influence on infiltration within SUDS (D).

3.1.2. Influence of groundwater on the SUDS functioning

For soil 1, the sharp water table rise beneath the infiltration basin and the northern swales (S2, S3, S6 and S7) significantly reduces infiltration within these SUDS (Figure 3-D1). This directly impacts infiltration (-149 mm compared to scenario FD_{SUDS}) and consequently runoff at the catchment scale (Figure 2-A1). For soil 2, as the water table rise beneath SUDS is less pronounced, local connections between SUDS and groundwater are far more limited (Figure 3-C2) and their consequences on the water budget are negligible (-9 mm of infiltration compared to scenario FD_{SUDS}; Figure 2-A2).

3.1.3. SUDS effects on transpiration

SUDS only slightly increase the transpiration for soil 1 and this effect is almost negligibly for soil 2 (Figure 2-A1 and A2). The relative influence on this flux is very low compared to that on infiltration (Figure 2-A1 and A2). This explains the sharp increase of groundwater recharge shown in Figure 3-B1 and B2.

For soil 1, a significant part of the transpiration increase is localized on surrounding green spaces, streets and parkings (Figure 3-E1) and occurs during summer (Figure 3-F1) i.e. when precipitation is no longer sufficient to satisfy the evaporative demand (Figure 3 C1). This increase amounts to about 50 mm at the domain scale. It is due to capillary upwelling from the water table that feeds the root zone, resulting in negative exchange volumes between unsaturated and saturated zones (Figure 3-B1). It thus depends on the magnitude of the water table rise (Figure 3-E1). The transpiration decrease in the upper part of the domain and within the infiltration basin (Figure 3-E1) is related to the root extraction conceptualization which assumes no water uptake for the root zone portions within groundwater. This effect is partially counterbalanced by an increase in evaporation from the surface storage, especially within the infiltration basin. SUDS influence on transpiration in surrounding areas is overall less pronounced for soil 2 (+9 mm; Figure 3-E2) because of the lower water table rise and of soil characteristics that limit capillary upwelling. The transpiration increase is concentrated within SUDS and, to a smaller extent, on surrounding streets (Figure 3-E2). The latter are indeed covered at 20 % by trees whose roots are little fed by direct precipitation (due to the impervious cover) and which are therefore more sensitive to even a slight increase in the water table level.

3.2. Role of sewer pipes on the hydrological functioning

The role of sewer pipes is evaluated by comparing the scenario with SUDS and sewer pipes (SP_{SUDS}) with that (i) with SUDS but without sewer pipes (GW_{SUDS}), and (ii) with sewer pipes but without SUDS (SP_{CONV}).

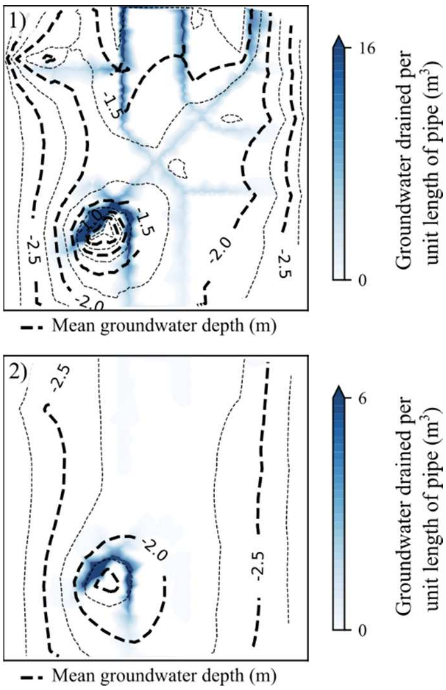

Figure 4: Spatial distribution of groundwater volumes drained by sewer pipes for the sandy loam (1) and the sand (2) over the whole simulation.

The water table rise due to SUDS results in groundwater seepages into sewer pipes reaching 83 mm for soil 1 and 7 mm for soil 2 (Figure 2-A1 and A2). For soil 1, the water table rises extensively above sewer pipes (set at a 2 m depth) which implies continuous seepages. They vary both locally (Figure 4-1) and temporarily (Figure 5-A1) following mounding fluctuations and more uniformly following seasonal groundwater fluctuations (Figure 5-A1). Conversely, for soil 2, the average water table elevation remains below pipes (Figure 5-A2 and C2). Seepages are therefore lower than for soil 1. They are controlled by local (Figure 4-2) and temporary (Figure 5-A2) connections between pipes and groundwater caused by mounding.

Groundwater drainage by sewer pipes in turn influence the water table rise caused by SUDS. For soil 1, the drainage significantly attenuates the overall rise (Figure 2-B1 and Figure 5-B1 and C1). The effects on mounding beneath SUDS are moderate but the attenuation is more pronounced between SUDS, particularly in the northern sector where mounding overlapped widely. For soil 2, the low groundwater drainage does not cause noticeable effect on groundwater levels (Figure 5-C2).

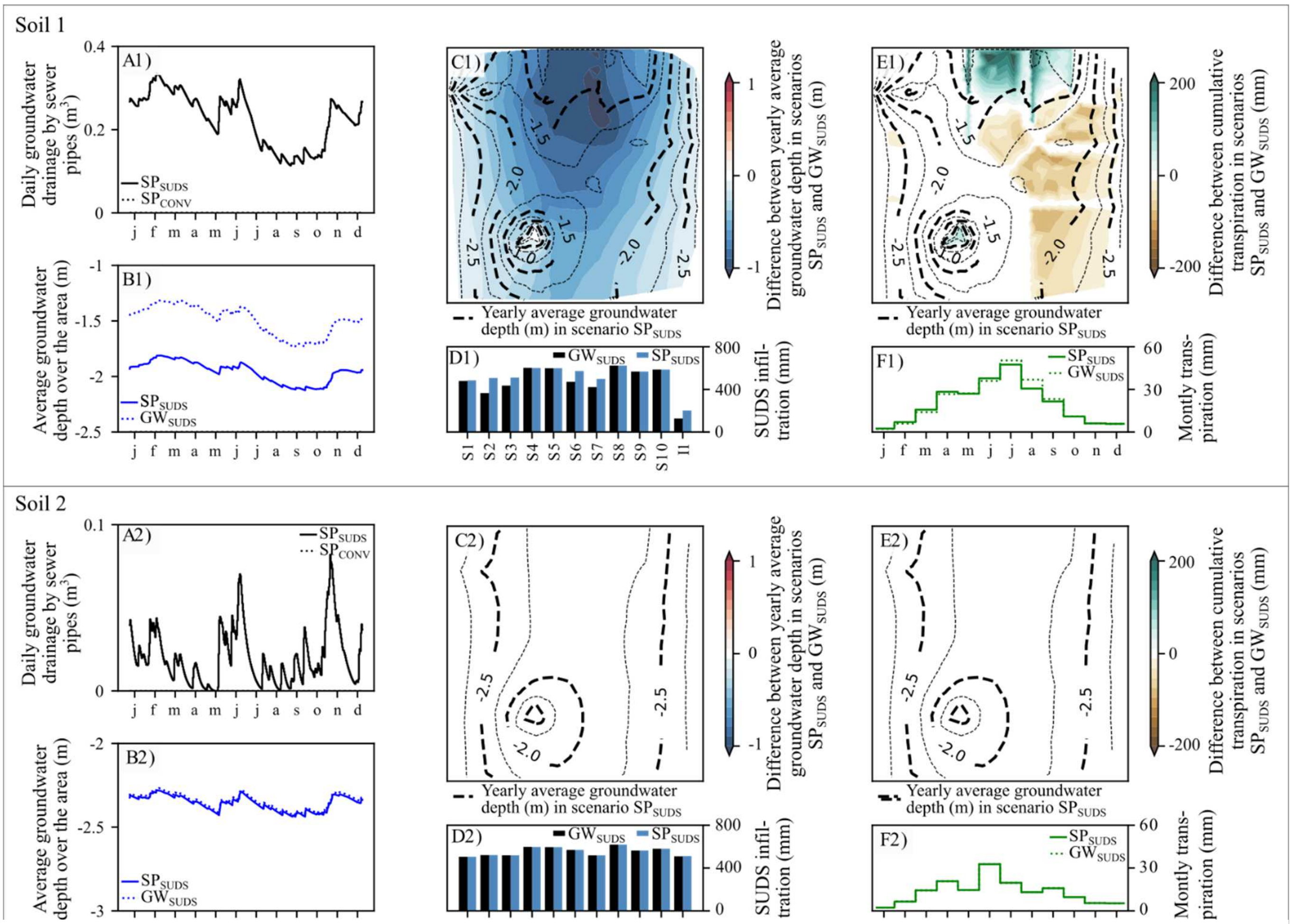

Figure 5 : Simulation results for the scenario SP_{SUDS} (sewer pipes only) for soil 1 (sandy loam) and 2 (sand). Comparison with scenario SP_{CONV} (corresponding scenario without SUDS) to assess the SUDS influence on daily groundwater drainage by pipes (A). Comparison with scenario GW_{SUDS} (no underground structure) to assess the sewer pipes influence on average groundwater depth over the domain (B), on yearly average groundwater depth at each point of the domain (C), on infiltration within SUDS (D), on cumulative transpiration at each point of the domain (E) and on monthly transpiration over the domain (F).

For soil 1, the attenuation of the water table rise reduces interactions between SUDS and groundwater, especially in the northern part of the domain. The infiltration within northern swales (S2, S3, S6 and S7) is therefore higher than without sewer pipes. This effect is weaker for the infiltration basin (Figure 5-D1). At the catchment scale, this results in a noticeable increase in overall infiltrated volumes (+42 mm compared to scenario GW_{SUDS}) and a corresponding decrease in runoff volumes (Figure 2-A1). For soil 2, SUDS functioning is not influenced by sewer pipes as the latter do not significantly affect water table levels (Figure 5-D2).

The sharp attenuation of the water table rise for soil 1 reduces SUDS effect on transpiration in surrounding areas (Figure 5-E1) during summer (Figure 5-F1). The transpiration increase in the infiltration basin and in the northern area (Figure 5-E1) originates from the conceptualization of root water uptake, the proportion of root within the water table being lower here. Overall, sewer pipes influence on transpiration remains minor (-6 mm compared to scenario GW_{SUDS}). For soil 2, sewer pipes do not influence the transpiration (Figure 5-E2 and F2) which is consistent with both their negligible effect on groundwater levels and the limited influence of the groundwater on transpiration (section 3.1.3).

3.3. Role of impervious foundations on the hydrological functioning

The role of impervious foundations is evaluated by comparing the scenario with SUDS and impervious foundations (IF_{SUDS}) with that (i) with SUDS but without impervious foundations (GW_{SUDS}), and (ii) with impervious foundations but without SUDS (IF_{CONV}).

The overall water table rise due to SUDS results in a greater foundation depth lying within the water table. In addition, the mounding beneath the infiltration basin significantly increases the difference in water table level between upstream and downstream limits of the foundations (Figure 6-A1 and A2). This increase reaches almost 1 m, for a maximum difference of about 2.6 m.

The impact of impervious foundations on the average water table elevation is overall negligible (Figure 6-B1 and B2). The barrier effect slightly increases the water table rise upstream of the foundations and slightly attenuates it downstream (Figure 6-C1 and C2). This effect is relatively small due to the low obstruction of the aquifer, the low hydraulic gradient and the closeness of imposed potential boundary conditions (Pujades et al., 2012).

The slight increase in the water table level beneath the infiltration basin (located upstream of the building) results in a slight decrease of the infiltration within this SUDS (Figure 6-D1 and D2). As downstream SUDS are not affected by the water table, the barrier effect does not influence their functioning. For soil 1, the infiltration in swale S6 located in the northern part of the domain is slightly increased (Figure 6-D1). The effect on the overall infiltration and runoff is negligible (-2 mm of infiltration for both soils compared to scenario GW_{SUDS}).

Similarly, the barrier effect negligibly affects transpiration within surrounding areas (Figure 6-E1 and E2).

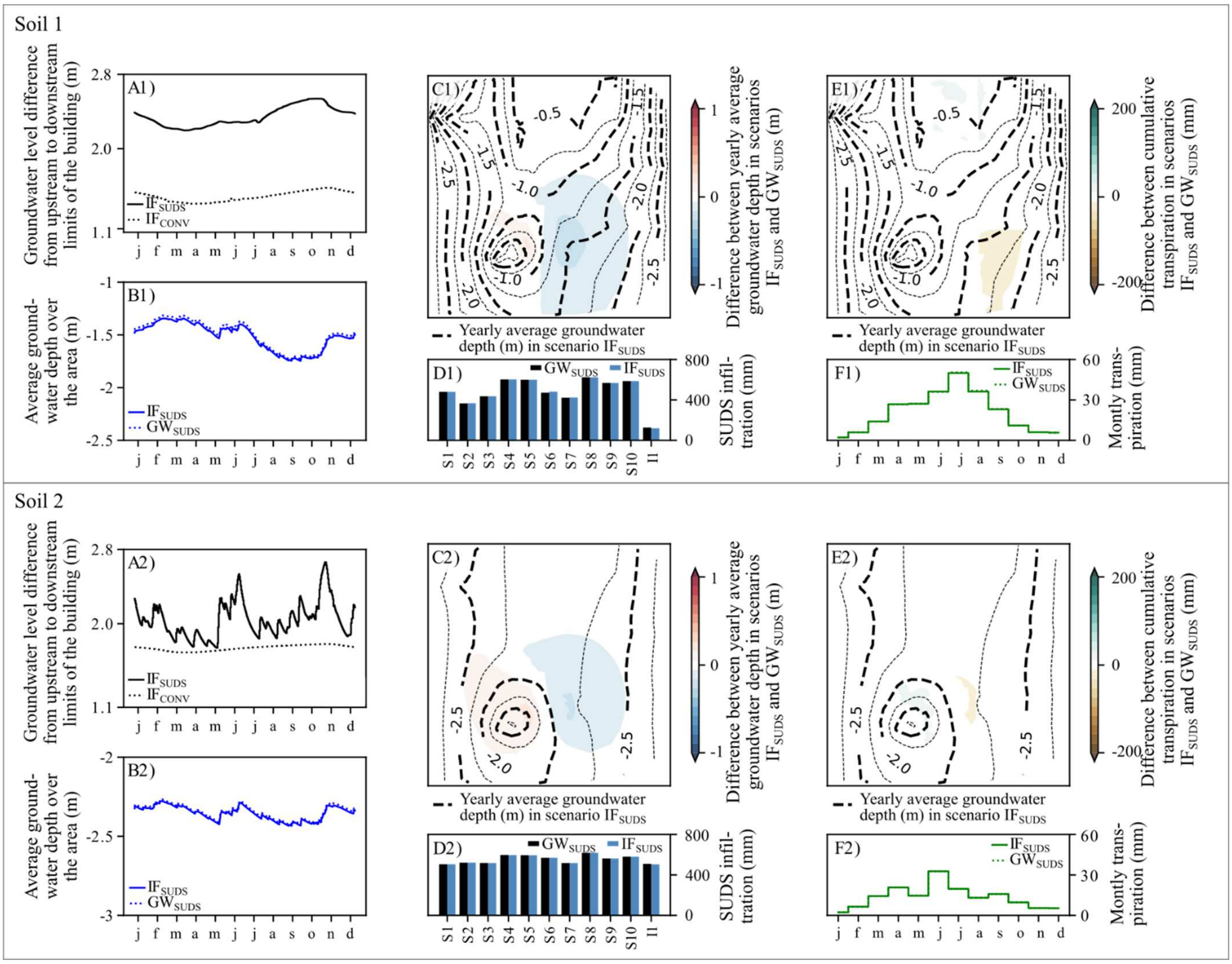

Figure 6 : Simulation results for the scenario IF_{SUDS} (impervious foundations only) for soil 1 (sandy loam) and 2 (sand). Comparison with scenario IF_{CONV} (corresponding scenario without SUDS) to assess the SUDS influence on groundwater level difference between upstream and downstream limits of impervious foundations (A). Comparison with scenario GW_{SUDS} (no underground structure) to assess the impervious foundations influence on average groundwater depth over the domain (B), on yearly average groundwater depth at each point of the domain (C), on infiltration within SUDS (D), on cumulative transpiration at each point of the domain (E) and on monthly transpiration over the domain (F).

3.4. Role of foundations equipped with a drainage system on the hydrological functioning

The role of draining systems (equipping foundations) is evaluated by comparing the scenario with SUDS and drained foundations (DF_{SUDS}) with that (i) with SUDS but without drained foundations (GW_{SUDS}), and (ii) with drained foundations but without SUDS (DF_{CONV}).

The water table rise caused by SUDS increases groundwater volumes drained by the foundation drainage system (Figure 2-A1 and A2). For soil 1, the drainage increases by 34 mm. It is relatively stable over time with a slight influence of seasonal water table fluctuations (Figure 7-A1). This is related to the quasi-permanent mounding beneath the infiltration basin located directly upstream of the foundations. For soil 2, the drainage increases by 94 mm, which is higher than for soil 1due to the higher aquifer transmissivity. The drainage varies following both seasonal groundwater fluctuations and rapid water table fluctuations related to the mounding beneath the infiltration basin (Figure 7-A2).

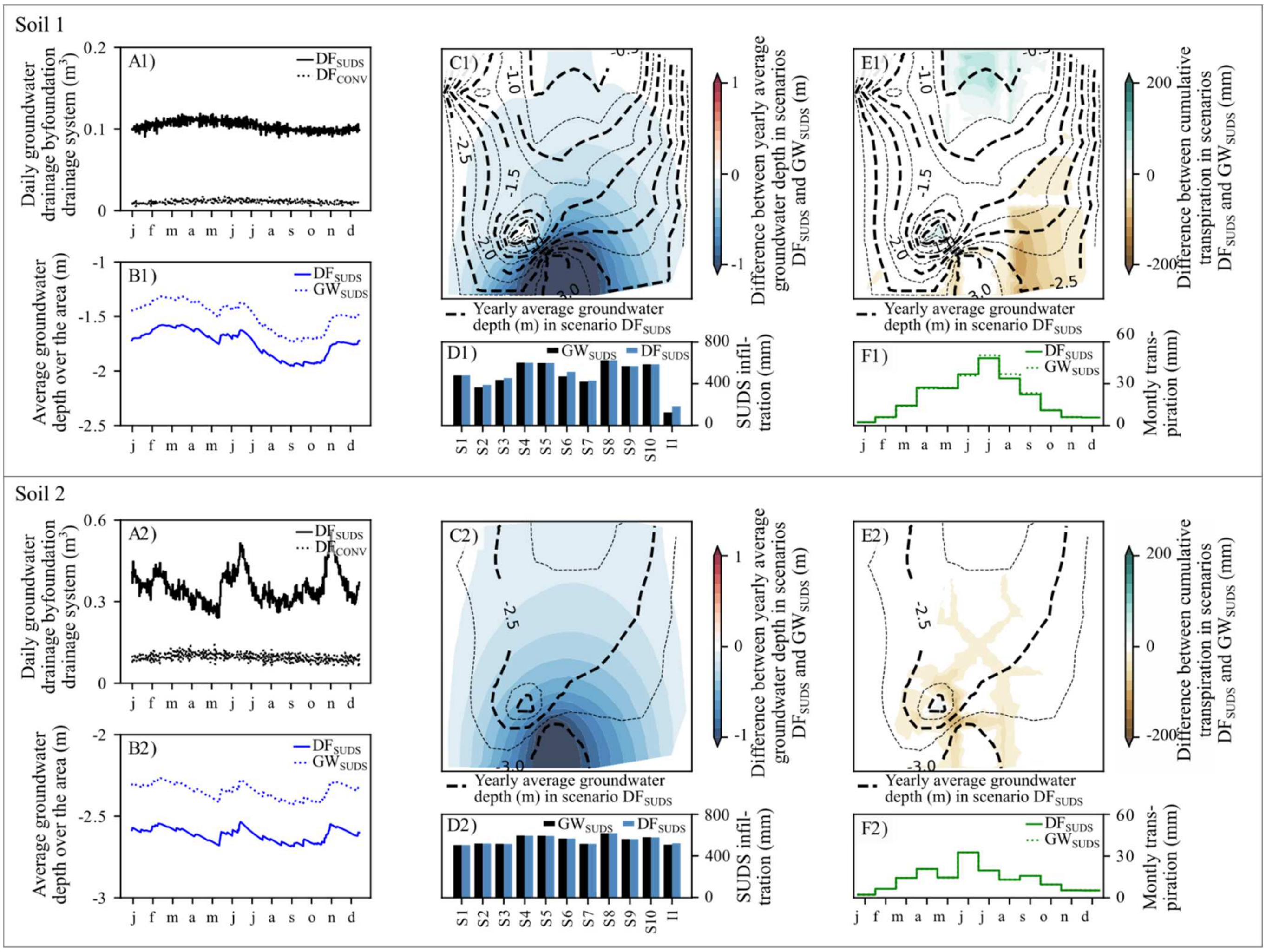

Figure 7 : Simulation results for the scenario DF_{SUDS} (foundation drainage system only) for soil 1 (sandy loam) and 2 (sand). Comparison with scenario DF_{CONV} (corresponding scenario without SUDS) to assess the SUDS influence on daily groundwater volumes drained by the foundation (A). Comparison with scenario GW_{SUDS} (no underground structure) to assess the foundation drainage system influence on average groundwater depth over the domain (B), on yearly average groundwater depth at each point of the domain (C), on SUDS functioning (infiltration within SUDS) (D), on cumulative transpiration at each point of the domain (E) and on monthly transpiration over the domain (F).

Although localized and shallow, the groundwater drainage significantly attenuates the water table rise associated with SUDS over the entire area with an increasing influence towards the foundations (Figure 7-C1 and C2). The attenuation is less pronounced beneath SUDS that highly concentrate infiltration, effect less marked for soil 2 (Figure 7-C). For both soils, the drainage strongly disturbs the shape of the piezometric surface and thus local groundwater flow directions (Figure 7-C).

The extensive attenuation of the water table rise reduces interactions between SUDS and groundwater and thus increases the infiltration within all SUDS affected by groundwater (Figure 7-D1 and D2). However, due to the shallow drainage depth and its limited spatial extent, the effect is localized near the structure (Figure 7-D1 and D2) and is moderate at the catchment scale (+23 mm for soil 1 and +4 mm for soil 2 compared to scenario GW_{SUDS}).

For both soils, the attenuation of the water table rise entails a low impact on transpiration in surrounding areas (except in northern area and in the infiltration basin as explained before) with an increasing influence towards the drainage system (Figure 7-E1 and E2). This influence is mostly concentrated in summer (Figure 7-F1 and F2) but the overall effect remains marginal (Figure 2-A1 and A2).

3.5. Cumulative effect of underground structures

The cumulative effect of all previously introduced underground structures is evaluated by comparing the scenario with SUDS and all underground structures (CE_{SUDS}) with that (i) with SUDS but without underground structures (GW_{SUDS}), and (ii) with underground structures but without SUDS (CE_{CONV}).

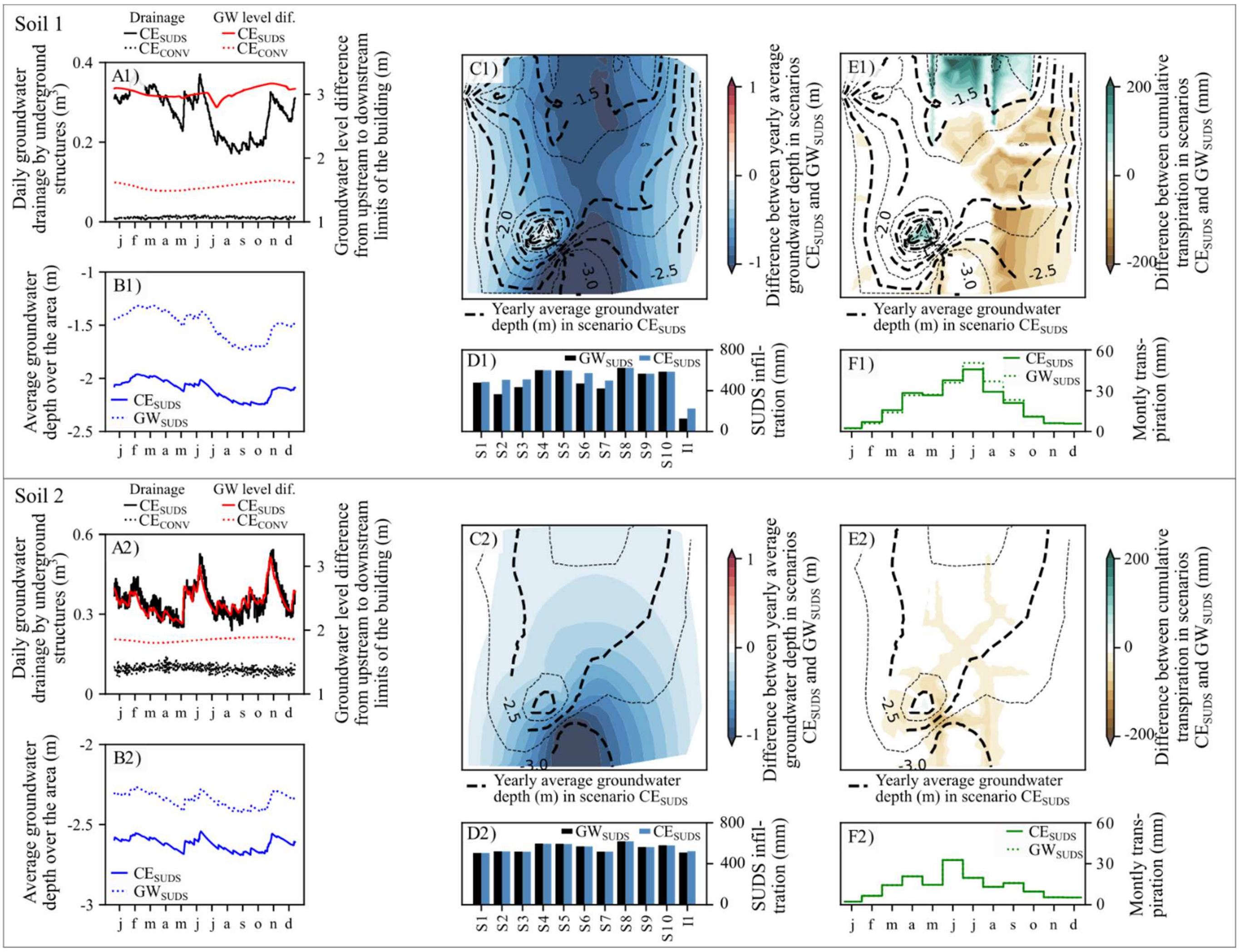

Figure 8 : Simulation results for the scenario CE_{SUDS} (cumulative effect of all underground structures) for soil 1 (sandy loam) and 2 (sand). Comparison with scenario CE_{CONV} (corresponding scenario without SUDS) to assess the SUDS influence on daily groundwater volumes drained by underground structures and on groundwater level difference between upstream and downstream limits of impervious foundations (A). Comparison with scenario GW_{SUDS} (no underground structure) to assess the cumulative effect of underground structures on average groundwater depth over the domain (B), on yearly average groundwater depth at each point of the domain (C), on infiltration within SUDS (D), on cumulative transpiration at each point of the domain (E) and on monthly transpiration over the domain (F).

The water table rise caused by SUDS entails an increase in groundwater volumes drained by the sewer pipes (+69 mm for soil 1 and +2 mm for soil 2) and the drainage system (+27 mm for soil 1 and +92 mm for soil 2). For soil 1, for which both structures cause significant drainage, the volume is lower for each structure taken individually (scenarios SP and DF) but cumulatively higher (Figure 2-A1 and A2). The GWD difference between upstream and downstream limits of the impervious building foundations reaches more than 3 m (with an increase of about 1.5 m). It is higher than in scenario IF as draining structures reduce the water table elevation more downstream than upstream (Figure 8-C1 and C2).

The cumulative effect of underground structures on the water table is dominated by draining structures (Figure 8-C1 and C2). For soil 1, the effects related to each structure overlap to create an extensive attenuation of the water table rise, more pronounced than for each structure taken individually (Figure 5, 7 and 8-B1 and C1). For soil 2, as the sewer pipes influence is negligible, the cumulative effect is identical to that of the foundation drainage system alone although the barrier effect introduces minor differences near the infiltration basin (Figure 7 and 8-B2 and C2). For both soils, the cumulative effect of underground structures significantly disturbs the water table shape (Figure 8-C1 and C2).

For soil 1, the sharp attenuation of the water table rise increases infiltration within all SUDS affected by the groundwater (Figure 8-D1) and reduces SUDS effect on transpiration in surrounding areas (Figure 8-E1). At the catchment scale, this results in a 50 mm increase in infiltration and a 8 mm decrease in transpiration compared to scenario GW_{SUDS}. These consequences are more pronounced than for each draining structure taken individually (Figure 5, 7 and 8-D1 and E1). For soil 2, the effect on both SUDS functioning and transpiration is identical to that of the foundation drainage system alone (Figure 7and 8-D2 and E2).

4. Discussion

4.1. Influence of model setup

The hypothetical catchment is designed to depict a realistic urban setting regarding land cover, subsurface features and hydrological processes. It allows assessing the individual effect of the different underground components, for different configurations regarding soil type or SUDS implementation, through pairwise comparisons of scenarios. However, the assumptions involved in the conceptualization of the catchment affect the magnitude of the interactions between surface and underground components. Results should therefore essentially be interpreted as an indication of interplays that may occur within shallow groundwater environments in the context of SUDS implementation.

The analysis focuses on an urban area of relatively low extension (0.25 km2), close to that of the neighborhood or small catchments. This scale is consistent with the objects and processes studied and the objectives. It is at the lower end of the range identified by Golden et al. (2017) for evaluating the effect of LIDs and their interactions and is consistent with the scales of analysis for papers analyzed in the literature review by Jefferson et al. (2017). However, this low spatial extension exacerbates the influence of hydrogeological boundary settings. The use of no-flow conditions on the lateral boundaries amounts to a symmetry assumption, likely to amplify groundwater level fluctuations.

Conversely, the fixed head boundary conditions on the upstream and downstream limits restricts groundwater level fluctuations and thus interactions with surface or subsurface features.

The two soil types considered aim at highlighting the contrasting influence of studied interactions depending on the transmissivity of the aquifer. The magnitude of these interactions is largely controlled by the characteristics of these two soils and using more extreme saturated hydraulic conductivity values would have led to amplified effects. Besides, the strong heterogeneities associated with urban soils, but also with, for instance, the sewer pipes conductance, the micro-climate and plant characteristics, are not accounted for in this study. While taking into account such heterogeneities was not relevant to the objectives of the study and would have complicated the analysis of the results, they are likely to affect spatial variability of observed effects and their influence should be examined in future research.

4.2. Potential interactions identified through this case study

Results are consistent with previous findings regarding SUDS effects on water table levels (Nimmer et al., 2009, Endreny & Collins, 2009) and potential consequences of the water table rise on SUDS efficiency (Locatelli et al. 2015) and transpiration by surrounding vegetation (Bonneau et al., 2018; Western et al., 2021). The magnitude of the latter effect depends on the potential of the water table to feed the root zone, i.e. on local groundwater depth and on soil characteristics. The results show that this effect can locally be significant during dry and hot periods, i.e. when the transpiration increase is often desired for instance to mitigate urban heat islands (Nuruzzaman, 2015). Nevertheless, the annual transpiration increase is relatively low compared to the increase in infiltration which suggests a relatively low effectiveness of infiltration strategies for restoring evapotranspiration volumes at the neighborhood scale.

Results suggest that the water table rise due to SUDS may sharply increase groundwater seepages into sewer pipes, which is consistent with the findings of Kidmose et al. (2015). Results show that this effect is reinforced by mounding beneath SUDS. Such interactions might prove to be widespread due to the common implementation of SUDS along streets (and so nearby sewer pipes). The interactions with these structures are, however, more complex than those represented in this study. In particular, seepage does not occur homogeneously but through punctual defects. Furthermore, the pipe-laying trench may have a significant influence, for example by temporarily storing volumes and delaying the drainage and the downward infiltration or by providing preferential pathways (Thompson et al., 2020). Results also suggest that local and global water table rises due to SUDS may significantly increase groundwater volumes to be drained, for example at the bottom of building foundations, which can among others have a direct impact on the sizing of related equipment. Water table rises also increase the depth of impervious structures lying into groundwater and the differential of this depth between opposite walls of the structure. In addition to an increased risk of seepage and basement flooding, this leads to a modification of the water pressure differential between opposite walls for which the structure may not have been designed (Pujades et al., 2012).

Conversely, underground structures affect groundwater flows and fluctuations. They may hence influence local interactions between groundwater and SUDS as well as the effects of SUDS on subsurface storage, groundwater flows and evapotranspiration. The barrier effect induced by impervious structures (e.g. car parks, tunnel and foundations) is likely to reinforce upstream and decrease downstream the interactions between groundwater and surface.

Underground structures that drain intentionally (e.g. draining systems, pumping) or not (e.g. sewer pipes) the groundwater attenuate these interactions by reducing localized and overall groundwater rise. Furthermore, such structures may capture a significant volume of the underground water storage and thus affect underground effects of infiltration strategies. For example, the GW volume drained by underground structures in the scenario CE (soil 1) represents ~40 % of the volume infiltrated in the SUDS. Moreover, these structures strongly disturb underground paths of the infiltrated water. In particular, the foundation drainage system in the DF and CE scenarios strongly modifies groundwater flows, with an inversion of downstream GW flows. Such structures are likely to reverse groundwater exchanges with neighboring streams and contribute to the fragmentation of flow systems (Attard et al., 2016b). They can therefore affect watershed-scale effects of infiltration strategies, for instance in restoring the base flow of nearby streams.

The results of these few scenarios illustrate the complexity of the hydrological response of urban areas to stormwater infiltration in shallow groundwater contexts. Future research should focus on systematically assessing the impacts of such practices at the watershed scale in a wider variety of contexts. The influence of urban soil heterogeneity or urban karst (Bonneau et al., 2017) should also be investigated, despite the difficulties involved in defining representative cases for these inherently site-specific features.

4.3. Preliminary insights for modeling urbanized areas with SUDS

Results suggest that the level of detail in the depiction of the underground compartment should be adapted depending on hydrogeological conditions and modeling objectives. When the aquifer has a sufficiently high transmissivity, the influence of the water table (and therefore of underground structures) on the surface hydrology is negligible. Obviously, the influence will also be negligible in cases where the water table is deep enough. Under such conditions, the assessment of SUDS impacts on surface and subsurface hydrology can be decoupled, at least partially. Studies focusing on surface impacts can neglect groundwater and subsurface features. Regarding the evaluation of subsurface impacts of SUDS, the variability of groundwater recharge should be considered (e.g. through partial coupling with a surface model) where SUDS involve groundwater level fluctuations likely to affect local flows and interactions with underground structures.

When the water table is likely to influence the surface hydrology (e.g. SUDS functioning, transpiration) modeling should consider two-way coupling between surface and subsurface in order to take into account the numerous retroactions between these compartments. In particular, the coupling between unsaturated and saturated zones should take into account capillary upwelling from the water table in order to more realistically depict the interactions between these zones and their influence on transpiration. Groundwater flow modeling should allow simulating the various fluctuations that influence both local interactions and impacts at broader scales. This involves, in particular, the use of sufficiently fine spatio-temporal discretization. Representing groundwater interactions with underground structures allows a more comprehensive assessment of the subsurface impacts of infiltration strategies and a more precise estimate of local influence of the water table on SUDS and transpiration. To identify processes and interactions that should be taken into account, their relative influence can be estimated using preliminary decoupled numerical simulations or analytical solutions (e.g. Hantush (1967) solution for mounding, Pujades et al. (2012) solution for the barrier effect).

Finally, comparison between the two modeled soils reveals a marked contrast for all effects investigated although their characteristics remain quite similar. This suggests that underground compartment characteristics, and potentially its heterogeneities, largely condition the interactions and thus potentially the overall hydrological functioning. Furthermore, it seems rather unlikely that sufficient hydrological data are available to calibrate the numerous processes specific to these environments in usual modeling conditions. This implies a high probability of compensations between parameters or processes, i.e. of finding contrasting configurations leading to similar matching to measurements. It may thus be advisable to avoid using single representations of the hydrosystem for modeling, but instead to use multiple working hypotheses approaches that integrate this uncertainty in composition and/or hydrologic functioning (Clark et al., 2011).

5. Conclusion

This study provides insights into the interplay between SUDS, groundwater and underground structures and into the detail level of the underground component representation required to assess infiltration strategies through hydrological modeling at the scale of small catchments. It relies on the numerical simulation of a set of scenarios based on a hypothetical urban area and varying by the soil type and the underground configuration.

Results indicate that SUDS may cause a significant rise of the water table. Simulated rise is strongly heterogeneous in time and space, with the formation of mounding beneath SUDS that interact with each other and with their surrounding environment. For the least permeable soil, the water table rise increases the transpiration in surrounding areas (+42 to +50 mm/y) but also reduces infiltration within SUDS (-99 to -151 mm/y). For both soils, the overall water table rise and mounding beneath infiltration devices increases groundwater seepage into sewer pipes and volumes drained by drainage systems (respectively +2 to +83 mm/y and +27 to +94 mm/y), the depth of impervious structure lying into groundwater and the differential of this depth between opposite walls of the structure (up to +1.5 m). Conversely, underground structures are found to strongly modify groundwater flow and level. For the least permeable soil, they significantly influence interactions between groundwater and surface (e.g. groundwater/SUDS interactions, effect on transpiration), which directly explains the above-mentioned range of variation in this case. Results thus indicate that in shallow groundwater environments, the overall effects of infiltration strategies at the neighborhood scale may strongly depend on interactions with underground structures. Potential effects on surface hydrology highlighted in this study suggest that, in the presence of low transmissive aquifer and shallow groundwater, the evaluation of SUDS functioning and of their hydrological effects at local and catchment scales requires modeling approaches that take into account the underground complexity and the interactions between surface and subsurface. Conversely, when the water table is deep or when the aquifer has a high transmissivity, decoupled models that focus on the compartment of interest may be appropriate.

This work provides preliminary insights into the hydrological functioning of shallow groundwater urban catchments with SUDS and the methods for their modeling. Further research should consolidate these findings by focusing on more diverse and realistic contexts. Such knowledge is required to better understand these systems and more accurately assess the hydrological impacts of stormwater infiltration strategies.

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Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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