Factors affecting the hydraulic performance of infiltration based SUDS in clay

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Abstract

The influence of small scale soil heterogeneity on the hydraulic performance of infiltration based SUDS was studied using field data from a clayey glacial till and groundwater simulations with the integrated surface water and groundwater model HydroGeoSphere. Simulations of homogeneous soil blocks with hydraulic properties ranging from sand to clay showed that infiltration capacities vary greatly for the different soil types observed in glacial till. The inclusion of heterogeneities dramatically increased infiltration volume by a factor of 22 for a soil with structural changes above and below the $CaC0_3$ boundary. Infiltration increased further by 8% if tectonic fractures were included and by another 61% if earthworm burrows were added. Comparison of HydroGeoSphere infiltration hydrographs with a simple soakaway model (Roldin et al. 2012) showed similar results for homogenous soils but indicated that exclusion of small scale soil physical features may greatly underestimate hydraulic performance of infiltration based SUDS.

Keywords

Infiltration; Stormwater modelling; SUDS

1 Introduction

Sustainable urban drainage systems (SUDS), also referred to as Water Sensitive Urban Design (WSUD), are used to mimic the natural water balance, often through stormwater infiltration into the soil. Infiltration based SUDS have various forms: rain gardens or infiltration basins collect stormwater directly at the surface or very close to it; whereas soakaways, or infiltration trenches, infiltrate stormwater underground (e.g. Hoyer et al. 2011, Freni et al. 2004). The utilization of the device allows for both quantitative and qualitative control of stormwater runoff during and after rain events and their design is based on inflow, outflow and detention water volumes (Freni et al. 2009, Campisano et al. 2011, Creaco and Franchini 2012). The efficiency of an infiltration device is dependent on the hydraulic properties of the surrounding soil.

Many soils in the Northern Hemisphere are derived from deposits of the last Weichselian glaciation (Houmark-Nielsen 1999). Though they generally have a high clay content and low matrix permeability, they are highly heterogeneous with hydraulic conductivities varying by several orders of magnitude (Fredericia 1990, Klint 2001, Nilson 2001).

Infiltration capacities also vary with depth due to changes in soil structure. Macropores like fractures, root holes and earthworm burrows have a major effect on infiltration, especially in low permeable soils (Klint and Gravesen 1999). For example, anecic earthworm species increase infiltration rates since they create semi-permanent to permanent vertical burrows into deep soil layers (Edwards 2004, Lee 1985). Root holes can also serve as important pathways for water flow in soils (Jarvis 2007) and have been studied by many authors. Meek et al. (1989) observed increased ponded infiltration rates by a factor of 2-3 under a 3-year old alfalfa stand compared to loose soil. Root holes are therefore likely to lead to increased infiltration rates in SUDS located in vegetated infiltration settings. In addition vegetation improves conditions for earthworms by increasing the C and N content in the soil (Smetak et al. 2011). Earthworm burrows often have a direct connection to the surface and a greater aperture than fractures and so have a greater effect on enhanced stormwater infiltration than fractures which usually start at greater depths. Macropores become hydraulically active in wet soil when the soil matric potential exceeds the macropores entry potential, but they do not conduct water in relatively dry soil, so that they can, depending on the degree of saturation, either serve as pathways for rapid downward movement of water or function as capillary barriers in the vadose zone (Wang and Narasimhan 1985). Preferential flow patterns can be identified with the help of dye tracer experiments (Jørgensen et al. 2002).

The $CaCO_3$ boundary usually lies in the upper 1.3 to 2.0 meters of the tills, with $CaCO_3$-free conditions above the boundary and $CaCO_3$-rich conditions below. The $CaCO_3$-free soil layers usually have a higher permeability and matrix porosities than the soil layers below, both due to the dissolution of $CaCO_3$ and the presence of densely spaced and randomly orientated desiccation fractures (Klint and Gravesen 1999, Rosenbom et al. 2009).

Methods are available to account for soil heterogeneity in models in order to simulate the performance of stormwater infiltration based SUDS (e.g. Roldin et al. 2012) but their performance is dependent on the accuracy of the input data and often hydrogeological models lack sufficient geological information (e.g. Hansen et al. 2013). Sophisticated hydrological processes such as macropore flow have not previously been incorporated into stormwater models (Elliott and Trowsdale 2007). However, since macropores are ubiquitous features in many types of sediments, it is important to include their characteristics in models if we wish to predict the hydraulic performance of infiltration based SUDS.

While root holes have not yet been included in models, empirical studies of rain gardens have shown increased infiltration around root holes compared to bare soils. These root holes have proven to be effective to prevent clogging of rain gardens from debris input (Virahsawmy et al. 2014).

Observations of infiltration based SUDS have shown that their hydraulic performance often differs from model predictions, for example infiltration capacities of rain gardens are often underestimated which results in oversizing (Backhaus and Fryd 2013). Soakaways have been shown to have high failure rates due to poor maintenance, inappropriate siting or high debris input (Woods-Ballard et al. 2007).

Fractures and biopores are ubiquitous in soils. This study aims to show that these small scale geological features have a significant effect on infiltration capacities, and should be considered when positioning and sizing infiltration based SUDS. The paper focuses on clayey tills and the effect on infiltration rates of small scale features like $CaCO_3$ poor and rich soil layers, earthworm burrows and tectonic fractures. Geological data characterizing a clayey till were employed with the discrete fracture model HydroGeoSphere (Therrien et al. 2009, Aquanty Inc. 2013) in simulations of variably saturated flow. Infiltration rates of four different homogenous soils were in a first step compared to infiltration rates produced with a simple soakaway model by Roldin et al. (2012) to investigate whether the soakaway model works well for homogeneous conditions. In a second step

infiltration rates of the homogenous soils were compared to infiltration rates obtained in structured, macroporous soils. Based on the findings this paper discusses implications for maintenance and siting of infiltration based SUDS.

2 Study area

To illustrate the importance of soil heterogeneity for SUDS performance data was obtained from a study area situated on an undulating till plain dominated by primarily basal sandy and clayey till, located approximately 20 km west of Copenhagen in Denmark. The site is representative for many formerly glaciated areas of the Northern Hemisphere. In a previous study Bockhorn et al. (2014) refined a geological map of the area on scales 200 m x 200 m using spear auger mapping to scales of 5 m x 5 m / 10 m x 10 m at a 0.8-1.0 m depth. Sediments samples ranged from sandy tills to lacustrine postglacial clays in a depression (Figure 1). The study area is surrounded by houses, parking lots and roads and therefore represents a common urban setting.

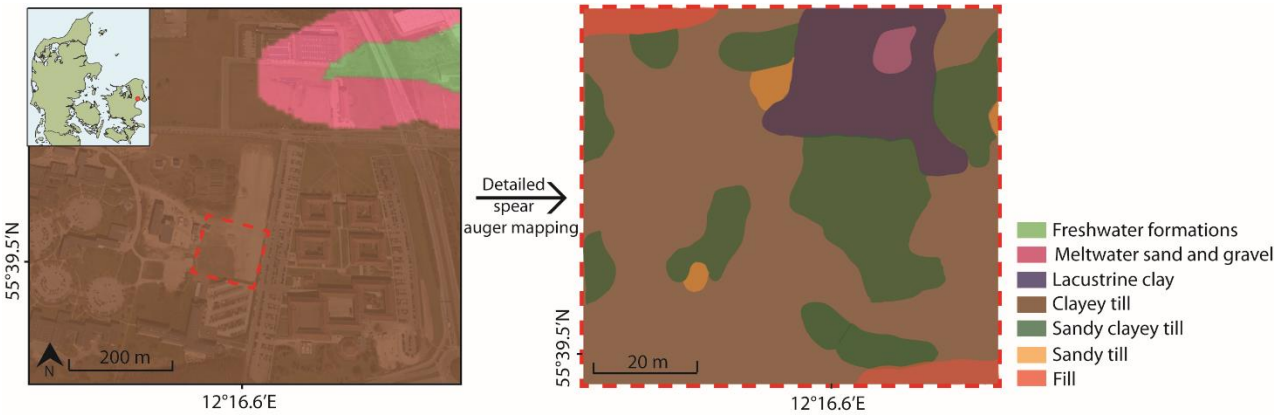

Figure 1. Study area on a traditional geological map with 200 m by 200 m resolution (left). Same area after refining with spear auger mapping with grid-sizes 5 – 10 m (right). Study area marked with red dotted line.

3 Material and Methods

3.1 Tracer test

To characterize the properties of local small scale soil physical features and to determine the macropore distribution, a tracer experiment was carried out in May 2012. The observed macropore distribution is incorporated into the modeling simulations for a realistic prediction of infiltration

behavior. Brilliant Blue was used as a tracer and applied to a 2.0 m x 0.5 m area. Before tracer application, the grass covered top soil was carefully removed to approximately 30 cm depth and a vacuum cleaner was used to clean the exposed surface to avoid smearing and clogging of the macropores by loose sediment. The trench was stabilized with a wooden frame and covered with gravel. Tap water was infiltrated over a period of several hours until saturated conditions in the soil column under the trench were achieved, and then the tracer was applied (20 l of Brilliant Blue solution), so that the dye only migrates into hydraulic active macropores. The trench was covered with a tarpaulin to minimize disturbance by outside factors. Four days after tracer application the site was excavated to a depth of 150 cm, corresponding to the location of the water table. The density of the dyed fractures was measured along vertical and horizontal scan-lines at 25 cm intervals on a vertical wall of the excavation pit. The density of dyed earthworm burrows was determined on horizontal planes at 25 cm depth intervals (Figure 2). The $CaCO_3$ boundary was determined by addition of 10% HCl.

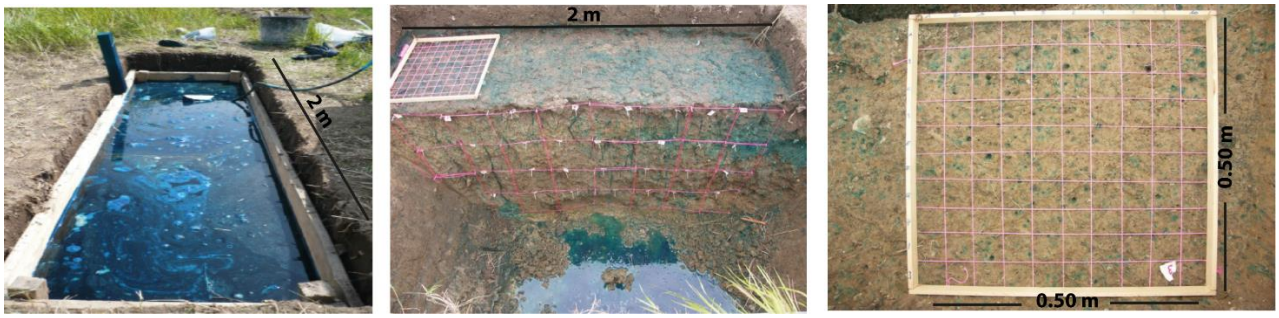

Figure 2. Left: set-up of tracer experiment to determine fracture and earthworm burrow distribution. Middle: exposure of vertical wall four days after tracer application for macropore analysis. Right: counting of earthworm burrows with the help of a 5 cm x 5 cm grid in a wooden frame.

3.2 Model simulations

This study employed HydroGeoSphere which is a three-dimensional control-volume finite element model that simulates surface water flow and unsaturated flow in discretely fractured or non-fractured porous media. Unsaturated flow is simulated by a modified form of Richards' Equation:

$$-\nabla\left(-\overline{K}\cdot k_r\nabla(\psi+z)\right)+\Gamma_{ex}\pm Q=\frac{\partial}{\partial t}\left(\theta_s S_w\right) \qquad (1)$$

where $\overline{K}$ is the hydraulic conductivity tensor, k_r is the relative permeability, ψ is the pressure head, z is the elevation head, ⌈ex is the subsurface fluid exchange rate with the surface domain, Q is a subsurface fluid source or sink, θs is the saturated water content, and S_w is the water saturation.

Fracture flow is simulated in two dimensions and a common node approach is used to couple flow in the fractures and matrix, based on the assumption of continuity of hydraulic head between the two domains. Flow velocities in the fractures are determined by the cubic law (Witherspoon et al. 1980). Retention and relative permeability for both fractures and porous media are given by van Genuchten functions or in a table form. For seamless integration of surface and subsurface flow, the porous medium is coupled with an overland domain and surface flow is described by the diffusion-wave approximation of the Saint Venant equations:

$$\frac{\partial \emptyset 0}{\partial t} + \frac{\partial(\bar{v}x0d0)}{\partial x} + \frac{\partial(\bar{v}y0d0)}{dy} + d0\lceil 0 \pm Q0 = 0 \qquad (2)$$

where $\emptyset 0$ is the surface porosity, $\bar{v}_{xo}$ and $\bar{v}_{yo}$ are the vertically averaged flow velocity in the x and y directions, respectively, d_o is the water depths, $\lceil_o$ is the fluid exchange rate with the subsurface, and Q_o is a surface fluid source or sink (Therrien et al. 2009).

The infiltration rates and emptying times simulated by HydroGeoSphere were compared to those obtained by the simple soakaway model presented by Roldin et al. (2012). The model of Roldin et al. (2012) is based on the soakaway mass balance:

$$n \cdot l \cdot w \cdot \frac{dh}{dt} = Q_{in} - Q_{out} \qquad (3)$$

where n is the porosity of the soakaway filling material, l is the length of the soakaway, w is the width of the soakaway, h is the water level in the soakaway, t is the time and Q_{in} and Q_{out} are the inflow and outflow rates from the soakaway. Q_{out} is the sum of the overflow rate and the infiltration rate. The infiltration rate f is assumed to be equal to the product between the hydraulic conductivity and the wetted area of the soakaway:

$$f = klw + k2h(l + w) \qquad (4)$$

where k is the soil hydraulic conductivity and klw represents the infiltration from the bottom of the soakaway whereas $k2h(l+w)$ the infiltration from the sides. The storage volume is described as $V=lwd/n$, where d is the height of the soakaway and n is the porosity of the filling material.

The same soil physical parameters were employed as were used in the HydroGeoSphere simulations, and the infiltration rates and difference in soakaway emptying time compared for the 2 models.

3.3 Model domains

To assess the variability of the infiltration capacity at the site, four 150 cm thick homogenous domains were set up to reflect the most dominant soil types sampled at the site Soil physical parameters were used to determine retention function parameters using the data provided by Carsel and Parrish (1988) (see Table 1). The same parameters were used in the soakaway models of Roldin et al. (2013).

The weighted mean for K_{sat} was determined by weighting each individual soil type by the size of the area covered.

Based on the information gained from the geological description of the excavation and the tracer test, the model was refined by adding additional soil physical features to the model domain, in the following sequence $CaCO_3$, fractures, earthworm burrows. The macropore distribution from the 1 m^2 large excavation pit was downsized to the 40.4 cm^2 large model area. The homogenous clayey till is the dominant sediment type on the study area and so was used for the base scenario.

In the heterogeneous simulations, the model was subdivided into two distinct layers (above and below $CaCO_3$ boundary). Randomly oriented desiccation fractures occur in the zone above the $CaCO_3$ boundary and were included in the model by embedding them into the matrix using the method proposed by Rosenbom et al. (2009). Tectonic fractures and earthworm burrows were added to the domain, with the distribution of macropores being taken from the results of the field investigation. All other parameters were obtained from the study of Rosenbom et al. (2009) (Table 1).

Table 1. Model input parameters used in HydroGeoSphere simulations. Parameters for sandy till, clayey till, sandy clayey till and lacustrine clay were obtained from Carsel and Parrish (1988) ('loamy sand', 'clay', 'sandy clay loam' and 'silty clay'). Parameters for soil layer 'above $CaCO_3$-boundary' and 'below $CaCO_3$-boundary', and macropore parameters were obtained from Rosenbom et al. (2009).

Medium	Parameter	Value	Medium	Parameter	Value
Sandy till *('loamy sand')*	K_{sat} [cm/min]	0.243054	**Clayey till** *('clay')*	K_{sat} [cm/min]	0.0033
	Porosity [cm^3 cm^{-3}]	0.41		Porosity[cm^3 cm^{-3}]	0.38
	Residual saturation [cm^3 cm^{-3}]	0.057		Residual saturation [cm^3 cm^{-3}]	0.068
	Van Genuchten Paramter:			Van Genuchten Paramter:	
	Alpha [1/cm]	0.124		Alpha	0.0088
	Beta	2.28		Beta	1.09
Sandy clayey till *('sandy clay loam')*	K_{sat} [cm/min]	0.02183	**Lacustrine clay** *('silty clay')*	K_{sat} [cm/min]	0.000333
	Porosity[cm^3 cm^{-3}]	0.39		Porosity[cm^3 cm^{-3}]	0.36
	Residual saturation [cm^3 cm^{-3}]	0.1		Residual saturation [cm^3 cm^{-3}]	0.070
	Van Genuchten Paramter:			Van Genuchten Paramter:	
	Alpha	0.059		Alpha	0.005
	Beta	1.48		Beta	1.09
Above $CaCO_3$ boundary	K_{sat} [cm/min]	0.324	**Tectonic fractures**	Aperture [cm]	0.01
	Porosity[cm^3 cm^{-3}]	0.36		Residual saturation [cm^3 cm^{-3}]	0.01
	Residual saturation [cm^3 cm^{-3}]	0.08		Van Genuchten Paramter:	
	Van Genuchten Paramter:			Alpha	0.04687
	Alpha	0.00698		Beta	2.29719
	Beta	2.0			
Below $CaCO_3$ boundary	K_{sat} [cm/min]	0.000108	**Earthworm burrows**	Aperture [cm]	0.4
	Porosity[cm^3 cm^{-3}]	0.31		Residual saturation [cm^3 cm^{-3}]	0.01
	Residual saturation [cm^3 cm^{-3}]	0.007		Van Genuchten Paramter:	
	Van Genuchten Paramter:			Alpha	0.1
	Alpha	0.00293		Beta	2.0
	Beta	1.07442			

3.4 Mesh and Boundary conditions

The same boundary conditions were used for all simulations. The nodal spacing in the z- and x-directions was 5.0 cm, but at the termination of the macropores the grid was refined to 0.1 with a multiplication factor of 1.5 above, below and adjacent to the macropores. The y-axis node spacing was 0.4 cm which equals the average diameter of the earthworm burrows.

Tectonic fractures and earthworm burrows were represented as 2D-planes in the model with a dip of 90 degrees and a uniform aperture along the macropore. Water retention characteristics are taken from (Rosenbom et al. 2009).

K_{sat} for the 2D-planes was given by $K_{fs}=\frac{\rho g}{12\mu}(2b)^2$ where ρ is the fluid density, g is gravitational acceleration, μ is the dynamic viscosity, $2b$ is the fracture aperture and K_{fs} is the saturated hydraulic conductivity of a single fracture [LT^{-1}], resulting in $K_{fs(\text{fracture})}$=0.817 cm/min and $K_{fs(biopore)}$=1307 cm/min.

The water table at 1.5 m depth served as the lower boundary as observed in the summer of 2011 when the fieldwork took place and was kept constant for the duration of the simulation. There is no flow through the sides of the model.

An infiltration flux of 0.25 cm/min was applied to the surface domain for 100 minutes and increased to 0.70 cm/min for the simulations of the heterogeneous and macroporous soil columns. The flux represents the stormwater runoff from a large nearby impervious area diverted to the smaller infiltration unit. A storage height was set to 30 cm for the infiltration flux of 0.25 cm/min and to 70 cm for the infiltration flux of 0.70 cm/min to prevent lateral surface flow.

The total simulation period varied from 50 hours to 80 days. The initial time step was 10^{-8} min with a maximum time step multiplier of 2.

4 Results

4.1 Tracer test

The results of the field investigations are presented in Figure 3. They include the distribution of hydraulically active earthworm burrows and tectonic fractures across the soil profile and the location of the $CaCO_3$ at approximately 130 cm depth, with randomly oriented desiccation fractures in the $CaCO_3$-free soil layer

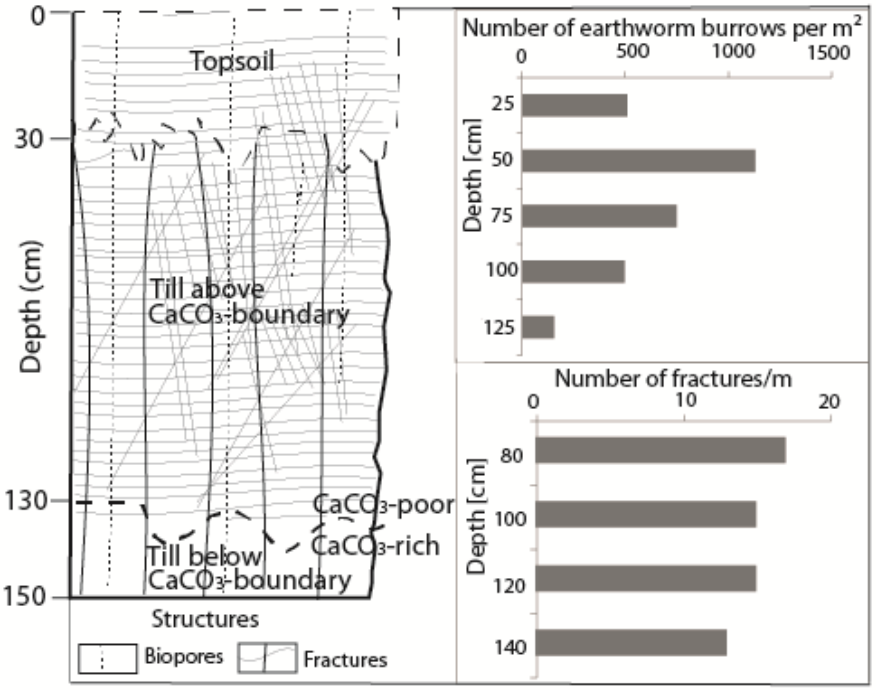

Figure 3. Geological log as determined in the excavation including distribution of macropore (vertical tectonic fractures and earthworm burrows).

4.2 Model results

The simplified model scenarios are shown in Figure 4.

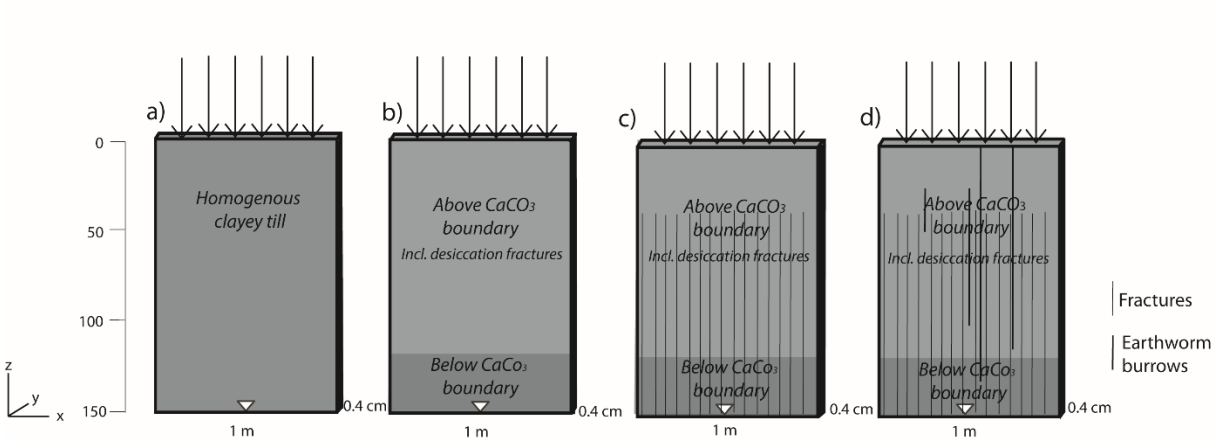

Figure 4. Different model domains according to geological description and macropore observations.

The weighted mean of K_{sat} for the study area was 0.0648 cm/min, compared to 0.0033 cm/min for the dominant soil type covering the large scale geological map. In this case, an incorporation of detailed knowledge on the sedimentary distribution increases the estimated K_{sat} by a factor of almost 20.

The infiltration rates from the HydroGeosSphere and Roldin et al. (2012) models are shown in Figure 5. These rates are of the same order of magnitude, demonstrating that the simple soakaway model gives infiltration rates in homogenous soils similarly to the HydroGeosSphere model. However, there is a significant difference in the initial shape of the hydrograph.

Results show the differences within the water balance for the different soil types with clear differences in infiltration behavior over time. Except for the sandy soil, stormwater input exceeds the infiltration capacity and water accumulates on the surface. By examining the area under the curves, the sandy soil can be seen to handle 94% more water than the lacustrine clay.

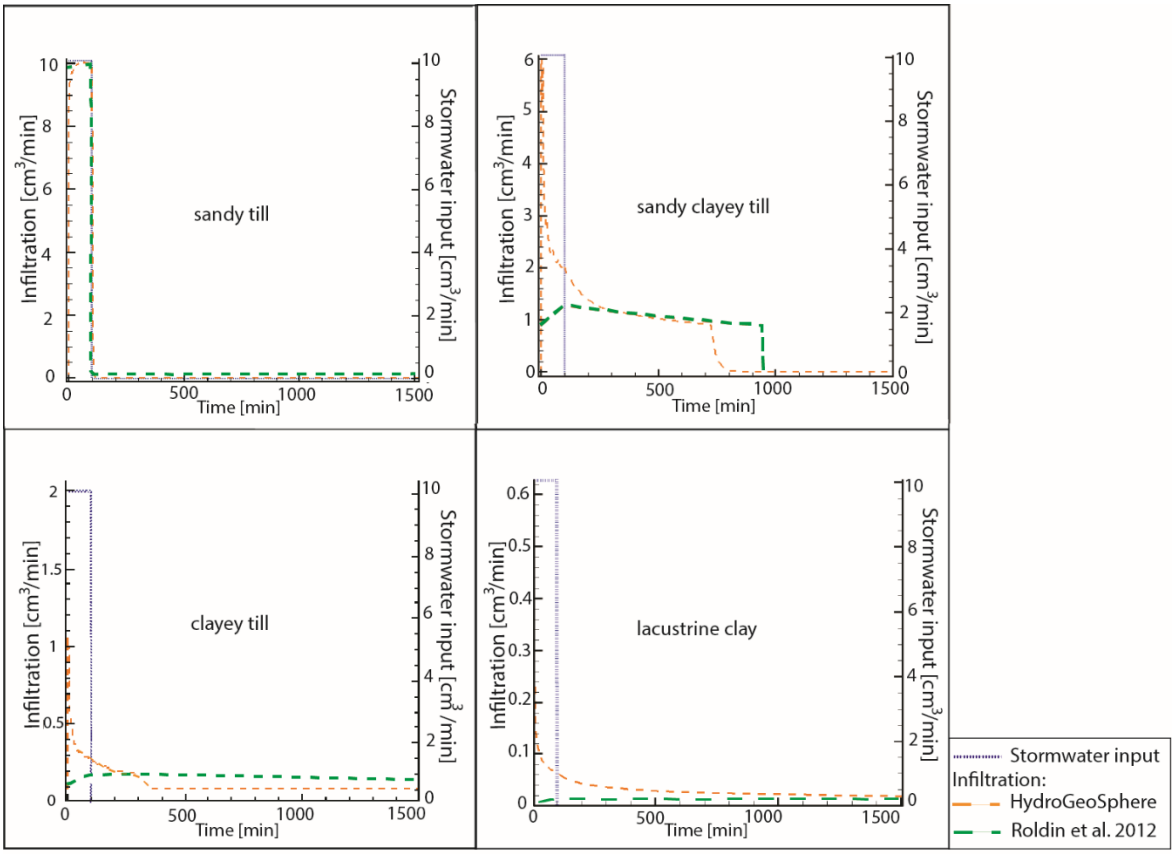

Figure 5. Infiltration rates into the four different soil types observed in the study area as simulated with HydroGeoSphere and the model from Roldin et al. (2012).

The soakaway emptying time obtained from the two models is shown in Table 2. The model from Roldin et al. (2012) approximates the results obtained from HydroGeoSphere within a range of approximately ±50%. This uncertainty is small compared to the uncertainty resulting from different soil types.

Table 2: Emptying times obtained from HydroGeoSphere and the model from Roldin et al. (2012).

	Roldin-model	Roldin-model assuming infiltration only from the soakaway bottom	HydroGeoSphere	Roldin-model/HydroGeoSphere
Sandy till	2 minutes	3 minutes	26 minutes	*
Sandy clayey till	14.1 hours	17.4 hours	12.5 hours	Overestimates 13-39%
Clayey till	4.2 days	5.1 days	8.6 days	Underestimates 51-41%
Lacustrine clay	42 days	52 days	75 days	Underestimates 44-31%

* It is not considered relevant to compare emptying time in the scale of minutes

Figure 6 displays the infiltration behavior for the heterogeneous clayey till scenarios presented in Figure 4 for two different stormwater inputs (0.25 cm/min over 100 min and 0.70 cm/min over 100 min).

As expected, infiltration capacity is increasing when soil structural features such as macropores are included. In the first scenario the capacity of biopore infiltration is not surpassed. The effect of preferential pathways on soakaway emptying times is presented in Table 3. For the second scenario emptying times vary between 17 days in a homogenous soil and 100 minutes in a soil with $CaCO_3$-boundary, fractures and biopores.

Table 3. Emptying times obtained from HydroGeoSphere for four different clayey till domains and two flux-boundary conditions.

	Homogenous clayey till	Clayey till with $CaCO_3$ boundary	Fractured clayey till with $CaCO_3$ boundary	Fractured and bioporous clayey till with $CaCO_3$ boundary
Hydrogeosphere (flux=0.25cm/min over 100 min)	8.6 days	29 minutes	21 minutes	0
Hydrogeosphere (flux=0.70cm/min over 100 min)	17 days	235 minutes	210 minutes	100 minutes

At a water inflow rate of 70 cm/min a 22-fold increase in infiltration volume was observed in the clayey till column when the $CaCO_3$ boundary and desiccation fractures were included as compared to the homogenous clayey soil. Infiltration shows a further increase in volume by 8% in a fractured soil and an increase by another 61% in a fractured soil perforated with earthworm burrows during the duration of stormwater input.

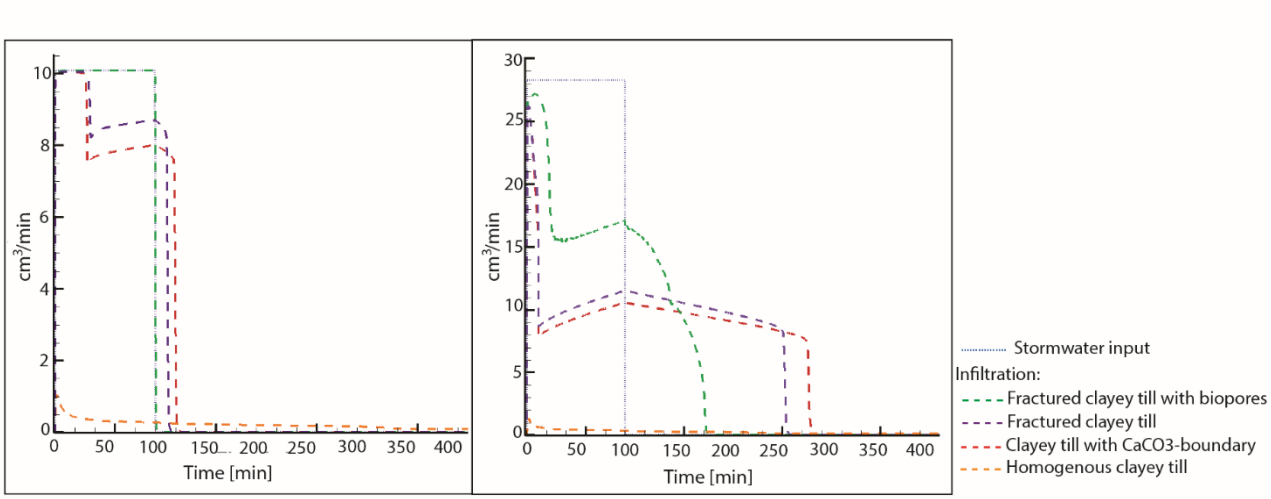

Figure 6. Infiltration rates for different clayey till domains and two inflow-boundary conditions. Left: Water application rate is 0.25cm/min. Right: Water application rate is 0.70 cm/min (right).

The importance of earthworm burrows for enhanced infiltration was also shown in the saturation profiles shortly before and after the rain event (Figure 7). Drainage (decrease in saturation) was faster along the biopores compared to drainage along the tectonic fractures and in the matrix.

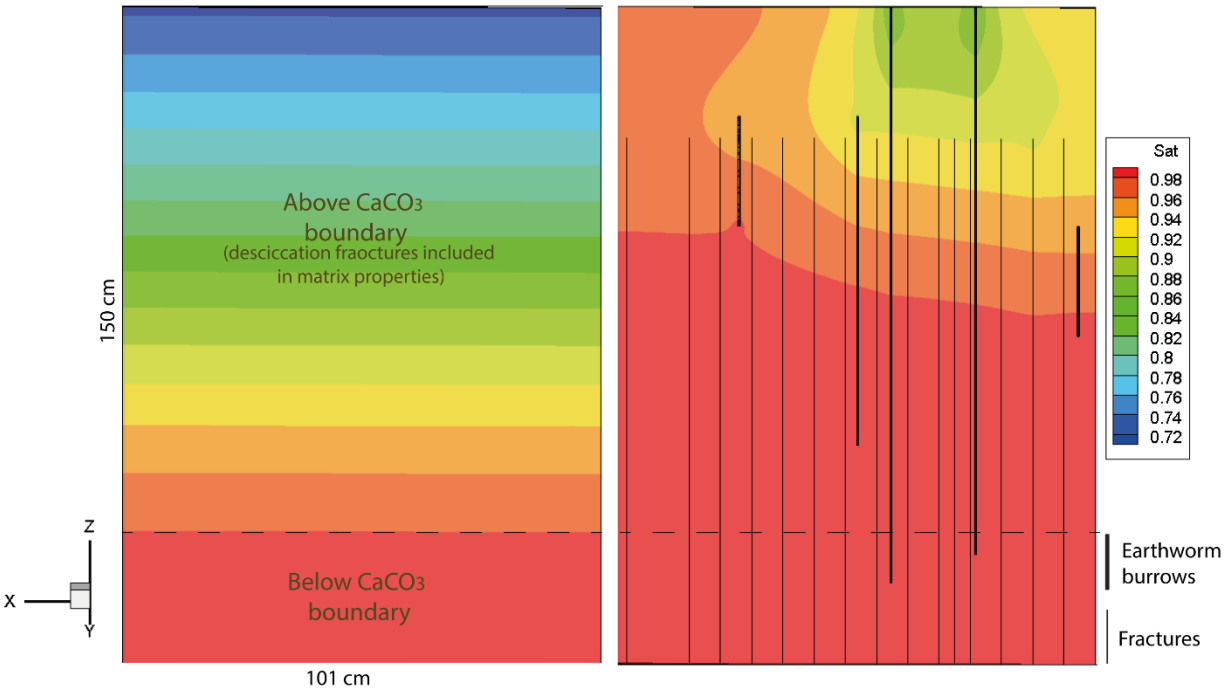

Figure 7. Saturation profile of clayey till column perforated with macropores before water application (left) and at termination of water application (right). Clayey till column model domain equals outer right column in Figure 5.

5 Discussion

5.1 Differences in model results

Significant differences in the initial shape of the infiltration hydrograph obtained by the Roldin model and HydroGeoSphere model are observed. This is because the model from Roldin et al. (2012) only considers the water level in the soakaway and not the matrix suction in the initially dry soil.

5.2 Model limitations

In these simulations no-flow boundary conditions were chosen on the model sides which may have led to an underestimation of the infiltration rates due to the presence of an artificial flow-barrier. In reality water would also move horizontally through the model boundary.

All macropores were represented as vertical 2D planes which might have led to overestimation of infiltration rates due to dominant vertical downward-flow. On the other hand, sub-horizontal freeze-thaw fractures and horizontal earthworm burrows can be interconnected resulting in a network of water pathways which may have led to underestimation of infiltration rates in the model. Studies by Tsakiroglou et al. (2012) document that flow in single fractures is not well represented by single vertical 2D planes but more likely by a 2D channel network.

Since this study was based on field observations at small scale with a well-defined geometry of the porous medium and fractures, a discrete fracture approach can best describe the flow conditions (Samardzioska and Popov 2005, Rosenbom et al. 2009). However, at larger scales it is difficult to account for every single fracture because of the computational cost of the simulations. For these cases it can be advantageous to employ a dual porosity approach (Samardzioska and Popov 2005). A dual porosity approach divides the domain into two separate pore systems, the porous matrix and the fractures, with separate hydraulic and transport properties. They interact by exchanging water and solutes in response to pressure head and concentration gradients (Gerke and van Genuchten 1993).

The simulations did not account for a potential biopore coating. Several studies indicate that walls of earthworm burrows can be lined with a thin hydrophobic mucus layer, secreted by earthworms. When water flows into a biopore, coating along the burrow walls can prevent its movement back into the matrix (Gerke and Kohne 2002, Rosenbom et al. 2009). However, no studies have been carried out yet successfully documenting the influence of biopore-coating on infiltration rates.

5.3 Risk of contaminant transport through preferential pathways

The simulations focused on the enhanced infiltration of stomwater runoff when macropores are present. However, it should be noted that increased infiltration rates enhance the risk of groundwater degradation by contaminant transport through the same preferential flow routes. Stormwater runoff often carries contaminants such as heavy metals, organic micro-pollutants, nutrients and suspended solids (Butler and Davis 2000). Experimental as well as modelling studies have shown that contaminants can be transported rapidly along fractures (e.g. Hinsby et al. 1996, Jørgensen et al. 1998, Sidle et al. 1998), sometimes even when matrix suction is high (Rosenbom et al. 2009). Infiltration of stormwater runoff should only be considered if either a special treatment facility upstream is installed (e.g. Göbel et al. 2008) or if non- or less polluted roof runoff is infiltrated. Moreover, infiltration devices should only be employed in areas far from aquifers of interest for drinking water supply.

5.4 Improved stormwater management practices in cities and maintenance implications

In this study the presence of earthworm burrows decreases the drainage time of the soakaway by 110 minutes. Rain gardens or infiltration basins may therefore have greater infiltration rates than subsurface soakaways and should be preferred if space allows. Moreover these systems can filter polluted stormwater runoff through biologically active soils and plants and so remove contaminants from the water (Davis 2007). Rain gardens and infiltration basins should be placed in locations where optimal living conditions for anecic earthworm species (e.g. Lumbricus terrestris) can be created, as the worms create deep, mainly vertical burrows for enhanced water flow into deeper soil horizons (Edwards 2004, Lee 1985), thereby improving the soil structure for increased infiltration. Smetak et al. (2011) showed that earthworm population density and diversity increases with age of the urban landscape and with the density of vegetation. Maintaining the soil structure by avoiding

tilling of the soil in and around the infiltration based SUD may therefore lead to improved hydraulic performance of the infiltration system over time. The performance of a newly soakaway can be improved by planting and the addition of earthworms to accelerate the process of soil structure development. The resultat bioturbation will increase the hydraulic performance of the raingarden over time and clogging of the system will be reduced.

In densely built urban areas, space is often insufficient for the installation of rain gardens which are large enough to handle water from all impervious areas. In such areas a combined design of a small rain garden functioning as a sand trap and water treatment device connected to a subsurface soakaway may be an option. In that way sediment loads into the soakaway will be reduced, preventing clogging of the device and thus prolonging its life expectancy.

6 Conclusions

Results of this study have shown that the siting and maintenance of infiltration based SUDS are important in clayey sediments. In this study soakway emptying times simulated on homogenous soil blocks varied between a few minutes and 75 days. The hydraulic performance of soakaways can be optimized by optimal siting through a detailed geological investigation (Bockhorn et al. 2014).

Simple soakaway models such as that of Roldin et al. (2012) were shown to be applicable to simulate infiltration rates and emptying times of soakaways in homogenous sediments. However, the simple soakaway model significantly underestimates infiltration rates in heterogenous (real) soils since they do not account account for preferential flow routes like fractures and macropores.

A detailed geological site investigation is needed for accurate prediction of soakaway performance in glacial deposits because of their large geologic heterogeneity. Areas consisting mainly of low permeable clayey sediments might have patches of sandy deposits which are optimal sites for the placement of infiltration based SUDS. Models employing standard soil physical parameters should be used with care as they do not always realistically describe site specific hydrologic properties.

In low permeable clayey soils, infiltration capacities are especially sensitive to the presence of small scale soil physical features such as horizontal and vertical fractures, earthworm burrows and structural changes across the soil profile. Upper soil layers typically have increased infiltration capacities, due to the presence of horizontal desiccation fractures above the $CaCO_3$ boundary and

the occurrence of earthworm burrows. Earthworm burrows are most beneficial for infiltration due to their greater aperture compared to fractures and because they often have a direct connection to the surface. Rain gardens may therefore operate with greater infiltration rates than subsurface soakaways and should be preferred if space allows, especially if they are designed so that they provide optimal living conditions for earthworms.

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