Use of geological mapping tools to improve the hydraulic performance of SuDS
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ABSTRACT
Most cities in Denmark are situated on low permeable clay rich deposits. These sediments are of glacial origin and range among the most heterogeneous, with hydraulic conductivities spanning several orders of magnitude. This heterogeneity has obvious consequences for the sizing of sustainable urban drainage systems (SuDS). We have tested methods to reveal geological heterogeneity at field scale to identify the most suitable sites for the placement of infiltration elements and to minimize their required size. We assessed the geological heterogeneity of a clay till plain in Eastern Jutland, Denmark measuring the shallow subsurface resistivity with a geoelectrical multi-electrode system. To confirm the resistivity data we conducted a spear auger mapping. The exposed sediments ranged from clay tills over sandy clay tills to sandy tills and correspond well to the geoelectrical data. To verify the value of geological information for placement of infiltration elements we carried out a number of infiltration tests on geologically different areas across the field, and we observed infiltration rates two times higher in the sandy till area than in the clay till area, thus demonstrating that the hydraulic performance of SuDS can be increased considerably and oversizing avoided if field geological heterogeneity is revealed before placing SuDS.

Key words | clay soils, geological heterogeneity, geoelectrical methods, stormwater infiltration, SuDS

INTRODUCTION
Sustainable urban drainage systems (SuDS) are used in several regions to handle stormwater runoff from urban surfaces in order to obtain a better water balance, to control diffuse pollutants and to prevent sewer overflow in areas with combined sewers. This almost worldwide observable trend of near-natural stormwater management often involves direct infiltration into the soil. Here, work efficiency of SuDS is dependent on the local hydraulic properties (Marsalek & Chocat 2002).

In Denmark many areas are covered by glacial sediments; 40% of these sediments are low-permeability clay tills where the infiltration of stormwater poses a huge challenge. Clay tills cover wide parts of the Northern hemisphere and were deposited by glaciers as ice-contact sediments. They range among the geologically most heterogeneous sediments (Houmark-Nielsen 1999, 2007). Generally, clay tills have a low hydraulic conductivity but they often incorporate sand lenses, macro pores such as earthworm holes and fractures. These structures can increase the hydraulic conductivity by many orders of magnitude and serve as hydraulic flow routes through an otherwise almost impenetrable layer (e.g. Fredericia 1990; Klint 2001; Kessler et al. 2012; Beven & Germann 2013).

The saturated hydraulic conductivity of clay tills lies in the range of approximately $1.0 \times 10^{-10} - 1.0 \times 10^{-4}$ m/s (Fredericia 1990). According to Danish guidelines for dimensioning of SuDS (Spildevandskomiteen 2015), an underestimation of the saturated hydraulic conductivity by a factor of 10 corresponds to oversizing the length of an infiltration trench or the area of a rain garden by a factor of two, other things being equal. Warnaars et al. (1999) showed large variations in the hydraulic behaviour of drainage systems at field scale where two infiltration trenches in close proximity to each other differed in their infiltration rate by one order of magnitude. Nevertheless, the impact of geological heterogeneity on drainage systems is still consistently

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ignored. Revealing geological heterogeneity at field scale usually requires labour-intensive and highly invasive methods. Non-destructive and less labour-intensive mapping tools that improve stormwater infiltration deserve to be studied.

Geophysical methods, such as electromagnetic induction systems and geoelectrical systems might stand as an efficient mapping tool to reveal small-scale heterogeneity for stormwater management practices. These methods have been used for a wide span of applications within environmental investigations (Pellerin 2002; Loke et al. 2013) from mapping or monitoring infiltration in the vadose zone or soil science experiments (Samouelian et al. 2005; Doolittle & Brevik 2014) to interpreting the vulnerability of aquifers in relation to the stratigraphy and heterogeneity of the Quaternary deposits (Sørensen et al. 2005; Kilner et al. 2005). Resistivity values can be correlated with certain sediment types where clays generally show low resistivities and sandy deposits high resistivities; Jørgensen et al. (2005) lists the resistivity intervals for common Danish deposits. Since the 1990s shallow electromagnetic and geoelectrical surveying have been proven to be powerful geological mapping tools if brought into line with drilling reference points (Nobes 1996). Although these methods have been widely used in site characterization (e.g. Nobes 1996; Pellerin 2002), they have only been reported to be used as a mapping tool for stormwater management designs in a few cases (e.g. Goutaland et al. 2007; Musa et al. 2010).

The objective of this study is to evaluate if the geological heterogeneity of the shallow subsurface (upper 1 m) on a clay till plain can be revealed at field scale by measuring the resistivity with a geoelectrical system. This will be undertaken by comparing the geoelectrical data with invasive geological and hydrological mapping tools. The overall aim is to identify most suitable areas for the positioning of stormwater infiltration devices on clay till plains and thereby minimize the overall requirement on the size of a SuDS element. Here, the hypothesis is that the hydraulic performance of SuDS can be increased significantly if field geological heterogeneity is taken into account when putting SuDS into practice.

METHODS AND FIELD EXPERIMENTS

All methods used in this study are presented in the order of occurrence. They comprise geoelectrical surveying, spear auger mapping and infiltration tests with a Guelph permeameter as well as with infiltration trenches. All surveys were carried out between spring 2012 and winter 2013 and are summarized in Figure 1.

The test site is approximately 100 × 100 m, neighboring a residential area of the municipality of Aarhus on the peninsula Jutland, Denmark. Geologically, the field site is situated on a clay till plain overlaying a buried valley system that serves as an important groundwater reservoir for the local municipality and in that way it represents a typical landform for many parts of Eastern Jutland (Nielsen & Japsen 1991).

Geoelectrical multi-electrode profiling

First, resistivity data were acquired using a geoelectrical multi-electrode system set up with a gradient array protocol (Dahlin & Zhou 2006) with a minimum electrode spacing of 1 or 2 m and a maximum current electrode distance of 72 or 144 m. All steel electrodes are connected via multicore cables to a multi-channel instrument and switching unit allowing data in several electrode configurations to be acquired simultaneously (Figure 2). Varying the current and potential electrode separations, geoelectric profiling and sounding are combined, returning a two-dimensional (2D) data-coverage along the inspected profile (Dahlin 1996). Six 80 m and one 160 m long profile were obtained across the field site (Figure 1). The field measurements were processed removing a few bad data due to occasionally poor electrode-to-ground contact, and inverted using two different inversion schemes resulting in resistivity models. A pseudo-3D approach, the 1D-SCI inversion approach (Viezzoli et al. 2008; Auken et al. 2014), where 1D 20-layer resistivity models with fixed layer boundaries as well as lateral and vertical constraints between the layer-resistivity in the adjacent models are inverted simultaneously, produced more reliable results than the ones obtained by a 2D inversion producing smooth resistivity models (Loke & Dahlin 2002). The 1D-SCI inversion resulted in a 20-layer 1D resistivity model for every 2 m along the profile.

Physical spear auger mapping

To confirm the geoelectrical data, a spear auger mapping campaign was carried out in a grid pattern (5–10 × 5–10 m), sampling the sediment to a depth of 1 m (Figure 1). This method is generally used for the systematic mapping of Denmark. It entails manually pushing an iron steel auger approximately 1 m deep into the subsurface. When pulled back up, a sediment sample remains in the notched tip of the spear, which can then be geologically described.
The field hydraulic conductivity of the site was determined with a Guelph permeameter. The Guelph permeameter is a constant head device based on the Mariotte siphon principle. It measures the hydraulic conductivity in a 40 cm deep borehole (diameter: 8 cm) with a constant water table. From the borehole, the water first spreads spherically and when saturated conditions are reached it infiltrates downward into the soil. We based our analysis on the analytical method given by Reynolds & Elrick (1986), which accounts for the ratio of water depth and borehole radius and includes data from tests performed with two different borehole water depths. Dimensionless shape factors were used according to Zhang et al. (1998), which minimize the uncertainty in the value of the estimated hydraulic conductivity (Zhang et al. 1998). Three approximately 50 m² large areas which differed in their determined electrical resistivity were selected. On each selected area a pair of Guelph permeameter measurements was conducted (Figure 1).

**Guelph permeameter**

The field hydraulic conductivity of the site was determined with a Guelph permeameter. The Guelph permeameter is a constant head device based on the Mariotte siphon principle. It measures the hydraulic conductivity in a 40 cm deep borehole (diameter: 8 cm) with a constant water table. From the borehole, the water first spreads spherically and when saturated conditions are reached it infiltrates downward into the soil. We based our analysis on the analytical method given by Reynolds & Elrick (1986), which accounts for the ratio of water depth and borehole radius and includes data from tests performed with two different borehole water depths. Dimensionless shape factors were used according to Zhang et al. (1998), which minimize the uncertainty in the value of the estimated hydraulic conductivity (Zhang et al. 1998). Three approximately 50 m² large areas which differed in their determined electrical resistivity were selected. On each selected area a pair of Guelph permeameter measurements was conducted (Figure 1).

**Figure 1** Location of geoelectrical profiles, spear auger mapping, Guelph permeameter and trenches used for infiltration measurements.

**Figure 2** Geoelectrical multi-electrode system set up at the test site.
Infiltration trenches

Based on the information gained from the previous investigations, three infiltration trenches on different areas across the field were established. All of them cover the areas where the Guelph permeameter measurements have been conducted (Figure 1). The trenches had identical dimensions of 15 m length, 0.17 m width and 1 m depth, and were filled with gravel (diameter: 16–32 mm; porosity: 0.25), corresponding to a maximum storage volume of approximately 640 l for each trench. A sketch of the trench design is shown in Figure 3. Water was added to the trench through a supply well (vertical perforated pipe) at one end of the trench until the desired water level (either 40 cm below ground surface (b.g.s.), or at ground surface) maintained a steady supply flow. The near steady-state infiltration rate was then measured in each trench measuring the constant flow rate with a digital flow meter (Brunata). Soil hydraulic conductivity was calculated by dividing the constant flow rate by the surface area of the trench. To assess the difference between top soil and mineral soil the hydraulic conductivity was measured at two different water levels in the trenches where one was at the surface and one 40 cm b.g.s. The experiments were repeated three times: on 24 September, 29 October and 16 December 2013.

RESULTS AND DISCUSSION

Geoelectrical multi-electrode profiling

Figure 4 shows in a map view the resistivity at a depth of about 1.0 m b.g.s. for all seven resistivity profiles as interpreted from the geoelectrical data. The resistivity values represent typical values for glacial sediments in Denmark (Jørgensen et al. 2005) and range between 30 and 120 Ωm. Moreover, the profiles show clear differences in their spatial distribution. The area around Trench 1 shows relatively low electric resistivities (around 40 Ωm); the area around Trench 2 shows medium resistivities (around 70 Ωm), and an area with relatively high resistivities can be observed around Trench 3 (around 120 Ωm).

Spear auger mapping

The sediments exposed from the spear auger mapping range from fills and melt water deposits over sandy tills and sandy clay tills to clay tills (Figure 4). The area around Trench 1 is dominated by clay till deposits, whereas the area around Trench 2 is covered by sandy clay tills and Trench 3 is mainly dominated by sandy tills. Each of the mapped sediments covers an area of approximately 50 m². In Figure 5, the three most dominant sediment types (sandy till, sandy clay till and clay till) in the three selected areas for the placement of the trenches are plotted against the layer resistivity at 0.6–1.0 m depth. The results of the spear auger mapping correspond to the geoelectrical data where sandy tills show a generally higher resistivity than the sandy clay tills and even greater differences in resistivity can be observed between sandy tills and clay tills.

Guelph permeameter and trenches

The results of the Guelph permeameter measurements point to significant differences within the test site with a hydraulic conductivity being almost two orders of magnitude higher in the sandy till than in the clay till (Table 1).

Measurements from the trenches show a similar picture to the results from the Guelph permeameter measurements. As expected, infiltration capacities increase from clay till over sandy clay till to sandy till (Table 1). For a water level of 40 cm b.g.s., the average infiltration rate in the clay till trench is 9.19×10⁻⁶ m/s while it is 1.80×10⁻⁵ m/s in the sandy till. For a fully filled trench, the average infiltration rate in the clay till trench is 1.14×10⁻⁵ and 1.62×10⁻⁵ m/s.
in the sandy till. In terms of stormwater management this means that an infiltration device can manage runoff from an area twice as big if placed in the most optimal area as compared to placement in the most widespread sediment type.

Hydraulic conductivities estimated with the Guelph permeameter and the trenches follow the same pattern, but the Guelph permeameter consistently returns lower values (Table 1). This is probably due to the fact that the trenches take a much bigger area into account than the shallow and narrow boreholes from the Guelph permeameter and comprise more than one sediment type. This is a confirmation of the hypothesis that geological heterogeneity on clay till plains influences the hydraulic conductivity already at field scale. Soil moisture conditions differed considerably among the 3 days of measurements and experiments may have not run long enough to reach steady-state conditions. This explains variations in estimated hydraulic conductivity among individual trenches on different days.

**Implications**

This study has focused on the geological heterogeneity of near-surface sediments of the upper 1 m. However, the geological heterogeneity of the till deeper than 1 m is also essential to understand because the presence of low-permeability sediments can hamper the escape of water to the aquifer. This may cause perched groundwater tables (Roldin et al. 2013) and thus inundation of the infiltration devices. Geophysical data can map the deposits to greater depth where the penetration depth depends on the system used. The resistivity information from the deeper part can be used in the evaluation of the location best suited for infiltration.

Infiltration tests were short-term experiments which did not take into account potential long-term effects of stormwater infiltration. Long-term field studies are required to assess the issue of the formation of perched aquifers. Since these field studies are time- and labor expensive, modeling experiments may be an appropriate alternative.

The geological field investigations showed that the conducted resistivity surveying provided reliable results to determine the optimal place for stormwater infiltration on a clay till plain and can therefore minimize the size requirements on infiltration devices. Similar results could be obtained carrying out the resistivity surveying with an electromagnetic induction method, which has very fast data
acquisition since no direct contact to the soil is required (Doolittle & Brevik 2014). Resistivity surveying is non-invasive and in particular the electromagnetic induction method is rather cheap to apply, for the most part, in comparison to the expected costs of conventional large infiltration devices. Its application is therefore particularly valuable in large low-permeability areas where large volumes of stormwater need to be handled. In a mapping concept it would not be necessary to conduct the spear auger mapping in a dense grid for the entire mapping area, but only in minor areas to put a control on the resistivity levels.

The geophysical methods can be applied in urbanized areas, although electrical installations may disturb the measurement very close to it. The geoelectrical method is less sensitive compared to the electromagnetic induction method.

**Table 1** | Summary statistics of the measured hydraulic conductivities for three soil type areas estimated from water infiltration in the trenches at two different water levels and from a Guelph permeameter. Measurements were conducted on three different days (M1–M3). The maximum value measured by each device is highlighted in bold. Locations of conducted experiments are shown in Figure 1.

<table>
<thead>
<tr>
<th>Clay till (m/s)</th>
<th>Sandy clay till (m/s)</th>
<th>Sandy till (m/s)</th>
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<tbody>
<tr>
<td>Arith. mean</td>
<td>9.19*10^-6</td>
<td>1.86*10^-5</td>
</tr>
<tr>
<td>Infiltration trench (water level at 40 cm b.g.s.)</td>
<td>9.19*10^-6</td>
<td>1.86*10^-5</td>
</tr>
<tr>
<td>Arith. mean</td>
<td>1.14*10^-5</td>
<td>1.62*10^-5</td>
</tr>
<tr>
<td>Infiltration trench (water level at surface)</td>
<td>9.19*10^-6</td>
<td>1.86*10^-5</td>
</tr>
<tr>
<td>Arith. mean</td>
<td>1.13*10^-5</td>
<td>1.62*10^-5</td>
</tr>
<tr>
<td>Guelph permeameter</td>
<td>6.39*10^-3</td>
<td>4.51*10^-8</td>
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<tr>
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**Figure 5** | Correlation between resistivity and sediment types at the site. Grouping the sediment types exposed through spear auger mapping into sandy till, sandy clay till and clay till and plotting the corresponding resistivity value at 0.6–1.0 m b.g.s. on a logarithmic scale returns an inverse linear relationship.
CONCLUSIONS

Resistivity surveying turns out to be an effective method to obtain knowledge on the distribution of different sediment types on heterogeneous clay till plains at field scale in a non-destructive and rather quick way.

As all geophysical methods include a significant degree of uncertainty if they are interpreted separately, we carried out an integrated analysis supporting the geoelectrical mapping with different geological mapping tools. The following methods were used to supply resistivity data in clay tills and to determine if resistivity surveying can provide reliable data to select optimal areas for stormwater infiltration:

- Spear auger mapping in 1 m b.g.s in a dense grid pattern (approximately 5–10 × 5–10 m) to reveal small-scale geological heterogeneity,
- Determination of field saturated hydraulic conductivity. We used a Guelph permeameter because this method is well established and determines the hydraulic performance below topsoil.

The integrated analysis of data from different mapping tools reduces uncertainty and can improve traditional geological investigations. The presented geological investigations can be significantly improved the hydraulic performance of infiltration devices in clay tills as the site-specific geology is taken into account. In this case, the hydraulic performance could be doubled due to the large geological heterogeneity of clay tills at field scale. This bisects the demands on the size of a SuD element and minimizes costs and size requirements. In this first study, open land with good access was chosen. Nevertheless, densely sealed areas in the city remain a challenge for finding suitable infiltration sites. Here, soil compaction and the lack of space are the main restricting factors. However, target areas for the application of our method may be parks that to some extent present the same degree of geological variability as our test site. This allows for rather direct transfer of results. In single family housing areas, the merged gardens may represent target areas as well as large roads with broad green verges.

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