Integrating soakaway infiltration devices in distributed urban drainage models – from allotment to neighbourhood scale

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ABSTRACT
A new model concept has been developed which includes a soakaway module coupled to the urban drainage model MIKE URBAN. The soakaway component calculates the infiltration rate based on water depth and soil properties for each time step, and controls the removal of water from the urban drainage model during runtime. This approach makes it possible to assess the impact of soakaways on urban drainage networks and related issues such as reduction of combined sewer overflows. The model was developed on allotment scale, and various upscaling methods have been tested for upscaling to block scale and neighbourhood scale. The field-saturated hydraulic conductivity of the soil was selected as scaling parameter, and it was found that the geometric average was most suitable to represent the sub-grid variability on larger scales.

KEYWORDS
distributed model; infiltration; soakaway; Sustainable Urban Drainage Systems; upscaling.

INTRODUCTION
Small-scale stormwater infiltration systems, such as soakaways and infiltration trenches, are often used as a means of reducing runoff and managing water resources in urban areas. Soakaways allow runoff from roofs, roads or other impermeable areas to be temporarily stored underground while slowly percolating into surrounding soils (CIRIA, 2007). They generally lead to significant decrease of stormwater in sewer systems and may therefore contribute to the mitigation of flooding problems due to surcharge of sewer networks, as well as enhanced recharge of groundwater resources.

Soakaways are one of many types of devices included in the alternative stormwater systems often termed “sustainable urban drainage systems” (SUDS), “water sensitive urban design” (WSUD), “stormwater best management practices” (BMP) or “low impact development” (LID). These types of structures are identified as an important part of developing a sustainable system for urban drainage (Chocat et al., 2007). However, to increase and spread the adoption of these methods, accurate and widely accepted models to estimate their impact on the urban hydrology are essential (Dietz, 2007).

Since flooding and surcharge of sewers are often local phenomena, which occur in single pipes and manholes or in a limited area during a limited period of time, a distributed and dynamic model approach is necessary to correctly assess the impact of soakaways on the sewer network. As discussed by Elliott and Trowsdale (2007), there is a variety of models for various WSUD elements, but when it comes to detailed distributed models, most elements can only be modelled indirectly or with limited accuracy. This paper presents a new modeling approach which addresses some of the above limitations, and is shown to represent the hydrological behavior of soakaways well.
If the impact of infiltration devices is to be assessed on a larger scale such as neighborhood or city scale, it is also important to consider methods for upscaling from individual lots to larger clusters. Thus, this paper also describes an upscaling method that has been developed based on two fictitious areas with 10 and 100 allotments respectively.

**METHODS**

**The coupled model concept**
A model for describing soakaway dynamics was developed and coupled to the urban drainage modelling software MIKE URBAN (MU). The coupled model is used to simulate the behaviour of a soakaway system in central Copenhagen, which was monitored in 1994-1997 (Warnaars et al., 1999). Simulations are also performed for two fictitious areas.

*The soakaway module.* The soakaway model is based on a general mass balance as described in equation 1.

\[
\frac{dh}{dt} = \frac{1}{l \cdot w \cdot \phi} \cdot \left( Q_{\text{in}}(t) - f(h,t) - Q_{\text{of}}(h,t) \right)
\]  

Equation 1

where \( h \) is water depth in soakaway, \( l \) and \( w \) length and width of the soakway, \( \phi \) the porosity of the filling material in the soakaway and \( Q_{\text{in}}, f \) and \( Q_{\text{of}} \) inflow rate, infiltration rate and overflow rate respectively. The infiltration rate is calculated according to equation 2. This formula has been shown to describe the infiltration from soakaways reasonably well (Mikkelsen, 1995).

\[
f = K_b \cdot l \cdot w + K_s \cdot 2h \cdot (l + w)
\]  

Equation 2

\( K_b \) and \( K_s \) represent the field-saturated hydraulic conductivity through the bottom and sides respectively, which can be estimated by an in-situ falling head tests (Warnaars et al., 1999). The value of \( K_b \) can be set to account for clogging effects that reduce the infiltration rate through the bottom. A schematic picture of the soakaway model is shown in figure 1.

![Soakaway schematic](image)

**The connection.** The connection between the soakaway module and MU is made through the built-in MU function UWC (User-Written Control) (DHI, 2008). This allows the user to control the simulation in a number of ways and exchange information with the MU model during runtime. The soakaways are modelled as basins in the MU model setup, and the UWC soakaway module can be set to identify the basins as soakaways and control the removal of water at each time step based on the infiltration model given in equation 2. Figure 2 shows a flowchart of the information exchange between MU and the soakaway module.
The field site and related model setup
The soakaway site that has been used for model verification is located in the Nørrebro area in central Copenhagen. It consists of 2 coupled soakaways (“North” and “South”), connected to the same inlet, and equipped with overflow pipes to the sewer network (the latter situated approximately 0.8 m above the bottom). Due to the location of the inlet about 0.44 m above the bottom level (see also Figure 3), the soakaways are interconnected and function as one when the water level is above this level. Dimensions and estimated parameters are listed in table 1.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l$</td>
<td>16</td>
<td>m</td>
</tr>
<tr>
<td>$w$</td>
<td>0.8</td>
<td>m</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>0.39</td>
<td>m$^3$/m$^3$</td>
</tr>
<tr>
<td>$K_{b,south}$</td>
<td>0.50</td>
<td>$\mu$m/s</td>
</tr>
<tr>
<td>$K_{b,north}$</td>
<td>0.81</td>
<td>$\mu$m/s</td>
</tr>
<tr>
<td>$K_{s,south}$</td>
<td>0.66</td>
<td>$\mu$m/s</td>
</tr>
<tr>
<td>$K_{s,north}$</td>
<td>2.75</td>
<td>$\mu$m/s</td>
</tr>
</tbody>
</table>

The listed $K$-values are based on averages of $K$-estimates from 6 events analyzed by Warnaars et al. (1999). Even though the two soakaways are very close together, their infiltration properties still differ significantly.

The performance of the coupled model was tested by simulating the water depths caused by a rainfall event that occurred in late September-early October 1996, and comparing with observed water levels. Data from flow rates recorded at the inlet was used as input to the model.
Fictitious model areas for development of upscaling method

In addition to comparison with observed data, the coupled model has been tested on three different scales (allotment scale, block scale and neighbourhood scale) in order to find a suitable upscaling method for the model. Two fictitious areas with 10 and 100 individual lots respectively were created, example shown in figure 4. The lots had identical characteristics except for the field-saturated hydraulic conductivity ($K$) which was individually sampled from a lognormal distribution with $\log_{10}(K) \sim N(-6, 0.5)$. Equal infiltration rates for bottom and sides were assumed, and $K$ is expressed in m/s. The assumption of a lognormal distribution is commonly found in literature (see for instance Tietje and Hennings, 1996) and the expected value of $10^{-6}$ m/s corresponds to the saturated hydraulic conductivity of silty sands (Fetter, 2001). A summary of the input data is listed in table 2. The list includes hydrological parameters for calculating input runoff to the soakaway.

When creating the lumped models, catchment areas and soakaway lengths were summed and all other input parameters were identical to the values on individual scale. The time of concentration listed in Table 2 is calculated automatically by MU based on catchment area and an average surface flow velocity of 0.3 m/s. Runoff calculations are made with a standard linear time-area method in MU (TA1) (DHI, 2008). The distance from the centre of the areas to the outlets is the same. The sub-grid variability of $K$ in the lumped model is represented by the parameter $K_{\text{effective}}$ which has been calculated in 5 different ways to see which method is the most suitable to represent the actual outflow from the area as calculated with the high resolution model. The parameters used for comparison of results are the peak flow rate in the outlet pipe and the accumulated overflow volume.

For each tested upscaling method, 50 simulations were run and the $K$-values on individual scale were re-sampled between each run. $K_{\text{effective}}$ was calculated in the 5 different ways based on the individual values of $K$. Three methods were averaging methods using arithmetic average, geometric average and harmonic average, and two methods were combination methods where $K_{\text{effective}}$ is a function of water depth in the lumped model according to Equation 3 and 4.
Table 2. Parameters and input data for the fictive area

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Allotment</td>
<td>Block</td>
</tr>
<tr>
<td></td>
<td>(1 soakaway)</td>
<td>(10 soakaways)</td>
</tr>
<tr>
<td>l</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>w</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>ϕ</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>A&lt;sub&gt;Catchment&lt;/sub&gt;</td>
<td>200</td>
<td>2 000</td>
</tr>
<tr>
<td>Runoff coefficient</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Time of concentration</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Initial loss</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

\[ K_{\text{effective}} = \frac{K_{\text{arithmetic}} - K_{\text{min}}}{h_{\text{max}}} \cdot h + K_{\text{min}} \]  

Equation 3

\[ \ln(K_{\text{effective}}) = \frac{\ln(K_{\text{arithmetic}}) - \ln(K_{\text{min}})}{h_{\text{max}}} \cdot h + \ln(K_{\text{min}}) \]  

Equation 4

where \( K_{\text{arithmetic}} \) is the arithmetic average of the \( K \)-values on individual scale, \( K_{\text{min}} \) is the smallest \( K \)-value, \( h_{\text{max}} \) is the maximum water depth in the soakaway before overflow occurs, and \( h \) is the water depth in the soakaway. Equation 3 is below referred to as “combination 1” and equation 4 as “combination 2”. The above equations were derived based on a comparison of overflow hydrographs from the different scales, where it could be seen that the start of an overflow event depends mainly on the smallest \( K \)-value (\( K_{\text{min}} \)) whereas the overflow when all soakaways are full is governed by the arithmetic average (\( K_{\text{arithmetic}} \)).

RESULTS AND DISCUSSION

Model performance on allotment scale and comparison with observed data

Figure 5 below shows observed water levels in the two soakaways in Nørrebro, and results from the model simulation. Note that water levels below 6 cm have not been recorded, as the pressure transducers used for monitoring were suspended a few centimetres above the bottom of the soakaways.

As seen in figure 5 below, the model captures the behaviour of the soakaways reasonably well. However, it seems to underestimate the infiltration rate when the water level is high. This phenomenon was also identified and discussed by Warnaars et al. (1999), and two main explanations were proposed:

- The soil at the site is somewhat layered, with the upper layer having a higher hydraulic conductivity than the lower
- The top soil is not wetted as often as the bottom soil and can be expected to have a lower initial water content, which affects the infiltration properties.

The \( K \)-value of the soil layer above the connection point of the soakaways was estimated by Warnaars et al. (1999) to be almost 40% higher than the \( K_r \)-value of the north soakaway below the connection point. This has not been taken into account in the model described in this paper, and may very well explain the underestimation of infiltration rate seen in the latter part of figure 5.
Figure 5. Model results compared to observed data, with $K$-values based on averages from 6 events analysed by Warnaars et al. (1999).

In the early half of figure 5 it can be seen that the water level is overestimated for the north soakaway and underestimated for the south. The reason for this may be that the inflow is not equally distributed between the two soakaways.

Future improvements of the model involves further development of the infiltration model, and may include adapting the infiltration model to take into account variations of $K$ with depth, or implementing a more detailed physically based approach such as the Green-Ampt model. Furthermore, the possibility of linking the developed model to a groundwater model will be examined, in order to simulate the two-way interaction between groundwater and infiltration rate.

**Upscaling methods and model performance on block and neighbourhood scale**

Comparisons of the total overflow volume and peak flow rate on allotment and block scale for the five tested upscaling methods are shown in figure 6. Figure 7 illustrates the same comparisons on allotment and neighbourhood scale for the upscaling method that is judged to give the best result on upscaling to block scale (geometric mean).

Figure 6 shows that the arithmetic averaging method leads to an underestimation in overflow volume in the lumped model. The harmonic average on the other hand overestimates the overflow volume, whereas the geometric averaging method seems to represent the overflow volumes relatively well. The latter also shows a lot better precision (i.e. less scatter) than the two former. As for the combination method, they show better accuracy than the arithmetic and harmonic averaging methods, but the scatter is still a lot higher than what is seen for the geometric averaging method.

When it comes to predicting peak flow rates, all five methods are relatively similar, generating peak flow rates within a relatively narrow range for the lumped model, compared to the wider range seen in the high resolution model.

The geometric averaging method still performs well when upscaling to neighbourhood scale areas, which is shown in figure 7. The precision is very high, although there seems to be a small deviation in accuracy, leading to a slight general overestimation of overflow volumes. The peak flow rate remains almost constant at lumped scale for any sample of $K$-values - between 33 and 34 l/s – compared to the peak rates ranging from 32 to 38 in the model on allotment scale.
Figure 6. Comparison of 5 different upscaling methods from allotment to block scale

Figure 7. Evaluation of geometric mean upscaling method from allotment to neighbourhood scale
To sum up, it seems as if the geometric average is a suitable method for upscaling of $K$. However, it should be noted that the above figures are all based on the same distribution of $K$, and the same rainfall event. Similar tests should be performed for other distributions and ranges of $K$ and several rainfall events, to ensure that the accuracy of the method is not dependent of any of these factors. A study by Kronaveter et al. (2001) concluded for instance in an upscaling test for infiltration facilities that low hydraulic conductivity led to larger differences in total infiltrated volume between scales compared to high hydraulic conductivity. This issue must thus be further investigated.

CONCLUSIONS
This paper presents a new modelling approach for soakaway infiltration devices coupled with a distributed urban drainage model, which can be used to evaluate effects of soakaways on urban drainage networks at a detailed level. The model has shown to be able to replicate the observed behaviour of soakaway elements in a sufficiently accurate manner. Upscaling from individual allotments to block and neighbourhood scale has been investigated with regard to the field-saturated hydraulic conductivity parameter, and the geometric average was found to represent the sub-grid variability most accurately under given conditions. However, the matter needs to be further looked into in future studies.

REFERENCES


