

Impact of model geology and resolution on urban local groundwater dynamics

Impact de la géologie du modèle et de sa résolution sur la dynamique locale des eaux souterraines en milieu urbain

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RÉSUMÉ

La modélisation intégrée fondée sur la physique des eaux de surface et souterraines est un outil important dans la gestion des systèmes d'eaux souterraines, mais elle est le plus souvent réalisée à l'échelle de grands bassins versants. Parallèlement, la gestion locale des eaux pluviales permet souvent à l'eau de s'infiltrer, ce qui a un impact sur la dynamique locale des eaux souterraines. À ces échelles, les exigences imposées au modèle pour représenter les processus locaux ne sont pas bien documentées. Cette étude détermine les impacts de l'utilisation de résolutions de modèles alternatives (1 m et 2 m) et de conceptualisations géologiques (simplifiées et réelles) dans un modèle intégré basé sur la physique sur les réponses locales des eaux souterraines dans un petit sous-bassin versant urbanisé. Les résultats ont montré des différences mineures dans les directions d'écoulement de surface ainsi que dans les niveaux des eaux souterraines localement sous une noue d'infiltration et sur un site plus vaste entre les résolutions de 1 m et 2 m. Modifier la représentation géologique a fortement influencé la réponse de la nappe. La dynamique locale était visible à l'aide d'un événement pluvieux de 20 mm pour les deux résolutions et représentations géologiques. Pour la modélisation future des eaux souterraines à plus petite échelle, une résolution de 2 m est recommandée afin de permettre un calibrage plus approfondi comme point de départ si les écoulements des eaux de surface sont vérifiés. Lorsqu'une représentation complexe de la réponse locale à court terme n'est pas nécessaire, une conceptualisation plus simple de la géologie peut être envisageable. Si une représentation détaillée incluant des couches à faible conductivité est appliquée, il est particulièrement important de connaître les taux d'infiltration, les niveaux naturels des eaux souterraines et la manière de définir les conditions limites appropriées du modèle.

ABSTRACT

Physically based integrated modelling of surface and groundwater is an important tool in the management of groundwater systems but is most often conducted at large catchment scales. At the same time local management of stormwater often allows water to infiltrate impacting local groundwater dynamics. For these scales the demands on the model for representing local processes is not well documented. This study determines the impacts of utilising alternative model resolutions (1m and 2m) and geological conceptualisations (simplified and real-world) in a physically-based, integrated model on local groundwater responses in a small urbanised sub-catchment. The results indicated minor differences in overland flow directions as well as groundwater heads locally under an infiltration swale and across a larger site between 1m and 2m resolutions. Altering the geological representation impacted the characteristics of the groundwater response substantially. Local dynamics were visible using a 20mm rain event at both resolutions and geological representations. For future groundwater modelling at smaller scales, a 2m resolution is recommended to allow for more extensive calibration as a starting point if surface water flows are verified. When complex short-term local response representation is not demanded a simpler conceptualisation of geology may be viable. If a detailed representation is applied that includes low conductivity layers, knowledge of infiltration rates, natural groundwater levels and how to set up appropriate model boundary conditions is especially important.

KEYWORDS

Geology, Groundwater, Urbanised area, Integrated model, Resolution

1 INTRODUCTION

While integrated modelling of surface water and groundwater is commonly used to aid in decision-making in the management of groundwater systems (Jakeman et al., 2016) these models are usually used at large catchment scales with few examples (e.g. Kalantari et al., 2014; Zölch et al., 2017) for smaller (sub)catchments and urbanised areas. Although local infiltration is a common approach for managing stormwater in urbanised areas (Fletcher et al., 2015) with respects to quantity and quality, its implications on groundwater quantity and quality are not well understood. Integrated modelling using distributed, physically based models such as Mike SHE has potential in supporting the implementation of these solutions by using physical properties to describe model components in individual grid cells. Variation in levels of detail both in spatial and vertical resolution and model conceptualisation allows for managing challenges regarding the spatio-temporal resolutions of both input data and physical processes (e.g. fast response of sewer, slow response of the saturated zone) and nonlinearity in the unsaturated zone. The choice of resolution is generally a balance between model runtimes and the size of the features of interest (e.g. LaBianca et al., 2023). The modelling of localised infiltration demands higher resolutions than typically used, but the impact of using input data sets of varying resolutions on model outputs in integrated models is not well documented. The present study aims to fill this gap by determining the impact of model resolution and saturated zone (SZ) and unsaturated zone (UZ) geometries on the dynamics of local groundwater in a small part of an urbanised area in Luleå, Sweden by comparing two geological conceptualisations at two resolutions for three rain events.

2 METHOD

The studied site is 210m x 350m, with the area of interest being the low point of a swale in the south-east used for stormwater infiltration and a point 11.5m from the swale (identified by red dots in Figure 1a. 1m and 2m spatial resolutions were implemented which resulted in 73,500 and 18,375 model cells respectively. Data for two summer rain events of 20mm in 10 hours (2025-09-20) and 37mm in 29 hours (2025-06-23/24) are used to generate profiles for a total of three events: the 20mm event (27.66mm/h peak, 2.04mm/h mean), the 20mm event multiplied by 2 to create 40mm rainfall (55.32mm/h peak, 4.08mm/h mean), and the 37mm event multiplied by 2 for a longer 74mm rain event (18.44mm/h peak, 2.56mm/h mean). The two geological conceptualisations included: model setup 1 (MS1) containing sandy soils, gravel building and road substructures as well as silt and clay layers; and model setup 2 (MS2) with a single sand layer to bedrock (Figure 1b). The SZ uses fixed elevations (m. asl). The UZ used a depth to top of layers based on terrain elevation. The boundary conditions in all directions and initial groundwater head were set at 4m asl., approximately 3m below the surface, and within the silt layer. At bedrock the bottom of the numerical layers acts as an impermeable boundary. Each model setup was modelled for each rain event at both spatial resolutions. The model run started one day ahead of the rain event and continued for approximately seven days after the rain event finished to allow for groundwater heads to stabilise.

3 RESULTS AND DISCUSSION

Model run outputs indicate that whilst local groundwater responses can be seen under most conditions including relatively common rainfall events, geological conceptualisation has a relatively larger impact on response characteristics compared to resolution. Modelled water balances showed minor errors for the overland and saturated zone components (<0.02 and <0.22%, respectively), and small to moderate errors for the unsaturated zone and subsequently total water balances (0.5–2.25%) with an exception for setup 2 (single sand layer) at 1m resolution for 20mm (8.15%) and 40mm (4.21%). The errors indicate a mostly numerically stable model, and the

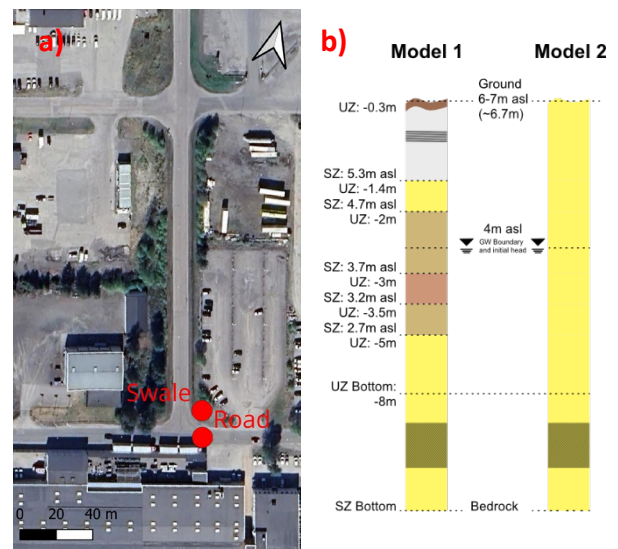


Figure 1: a) Model domain and points observed and b) conceptual geological model for SZ and UZ soil layering under the swale. Brown (UZ only) = topsoil; Gray = Infill gravel under impermeable surfaces or natural sand; Yellow = Sand; Brown = Silt; Taupe = Clay; Wavy = Variable height depends on surface level and bedrock.

small numerical instabilities are not considered to impact the conclusions. Analysis of overland (OL) flow, standing water levels and flow directions using Mike SHE flow path arrows (not shown) in the areas surrounding the swale at 1m and 2m resolutions did not show any notable differences. It should be kept in mind that the OL flow is simplified in this case: the area does not include roadside curbs which are likely to create larger differences between 1m and 2m resolutions, since the lower resolution makes accurate representation of small local differences challenging, often leading to shifts in location or lower refinement of terrain height.

Figure 2 shows the groundwater heads, standing water and infiltration at the deepest point of the swale and on the road to the south (red dots in Figure 1) for the 20mm and 20 × 2mm model runs for all model setups. In terms of impact of the UZ and SZ geometries, MS2 (singular sand layer) showed a significantly stronger and faster groundwater response than MS1. The difference in the time until peak (~52h (MS1) and ~5h (MS2) for 20mm event) can best be explained by the topsoil layer in the first 30cm of the swale and silt layer present in MS1. The topsoil has a lower hydraulic conductivity ($K = 3.7e-6m/s$) than sand ($K = 6.5e-5m/s$) and could thus limit infiltration rates from the surface. Additionally, the water table is located within the silt layer, which has a lower conductivity set ($K = 1.9e-5m/s$) and thus increases the delay further and limits horizontal flow within the saturated zone. The topsoil further leads to prolonged standing water in MS1 which impacts model runtimes substantially. The fast and strong response of the head in MS2 was caused by the highly conductive sand letting water infiltrate and percolate rapidly, meaning there is a direct relationship between rainfall intensity and GW heads. The GW drains away from the swale following the peak due to the sand’s high conductivity.

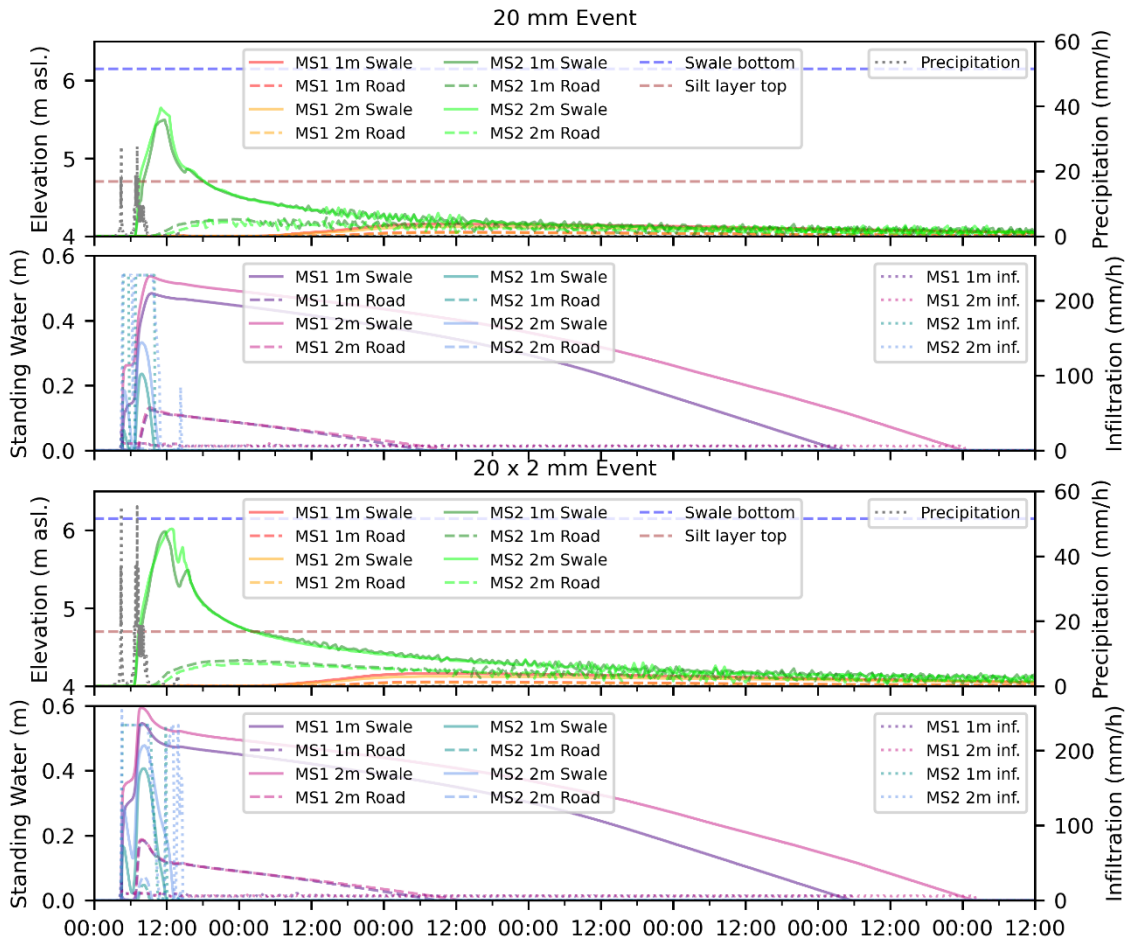


Figure 2: Groundwater heads, precipitation rates, standing water and infiltration in two points in the area of interest from 2025-09-20 (one day into simulation) to 2025-09-26 12:00 (stabilised levels, simulated to 2025-09-29).

Mounding effects are visible in all runs, though the increases in heads are small in MS1. The time until peak and strength of the peak differ significantly between model setups, caused by the 30cm soil layer and groundwater level lying in the silt layer. The impact of resolution is minor on groundwater heads, and slightly larger on standing water levels. The event rainfall volume causes a larger increase in heads (more so for MS2) but does not change the characteristics of the response.

In MS1 the slower percolation causes a shift and smoothing of the GW head response to the rainfall. As the groundwater response of the 74mm event largely follows the same patterns established in the 20mm and 37mm events it is not included in the figure. The head increase is prolonged due to the longer event duration, however.

Mean groundwater heads (data not shown) over the whole site increased slightly due to the swales along all roads resulting in infiltration across the whole area. The average head increases between 10 and 20cm at its peak in MS2, and 2 to 4cm in MS1. Heads decrease slowly starting approximately 2.1 days (MS2) to 4.1 days (MS1) after the event start and remain slightly elevated at the end of the runtime. Boundary conditions impact this behaviour, and the 4m constant head boundary is thus a factor in this slow decrease. The behaviour is expected at larger scales too, however, where open water bodies ideally act as constant head boundaries. The model resolution did not have a significant impact on the results, with mounding noticeable in both setups, at both resolutions, and all three rain events (see Figure 2); heads increase at both points, but the road heads increase by 2–3% (MS2) or 25–30% (MS1) of the peak at the swale. Across the entire site the differences were relatively minor (typically less than 1%), with a peak of 6% in MS2 at 40mm rainfall. As the heads decrease, the differences diminish.

4 CONCLUSION

This study aimed to determine the impact of alternate model resolutions and model SZ and UZ geometries (in this case presence of layers with limited conductivity) on the dynamics of local groundwater in integrated, physically based models applied at an urban sub-catchment scale. Results showed clear mounding under stormwater management swales at 1 and 2m resolutions, and generally small differences between the resolutions regarding groundwater heads and standing water levels. Two-meter spatial resolution is therefore recommended as a starting point for urban models without complex surface flows, if terrain models are verified to produce correct flow paths. The substantially lower runtimes required for 2m resolution can make more extensive sensitivity analyses and calibration procedures feasible.

Meanwhile, differences caused by the geologic structure of the SZ and UZ were more substantial. The simulations highlighted that a more detailed representation of the geology can have a major impact on the model both for overland flows (impacting runtimes) and in the subsurface (silty and clay layers limiting horizontal and vertical flow in contrast to high permeability allowing for rapid fluctuations). This did not affect long-term groundwater heads substantially. However, the level of detail required for subsurface components of the models could differ dependent on the focus of each study (e.g. pollutant transport requiring detailed presentation of flow paths and therefore geology, including manmade elements). The results of the simulations using the detailed geology (MS1) were also substantially influenced by the groundwater head being in the silty layer, if such layers are implemented the importance of setting accurate initial GW levels and boundary conditions increases further.

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