Large-scale urban hydrological modelling at high spatial resolution: requirements and applications

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Abstract

Urbanization and associated increase of imperviousness alters the hydrological cycle of urbanizing catchments. Low Impact Development (LID) tools have been developed and applied to mitigate these hydrological impacts. Hydrological models are one way to evaluate the performance of LID tools before their implementation. As these tools represent small-scale hydrological processes, hydrological models used in assessment require a high spatial and temporal resolution in their process descriptions. Both flow and rainfall data at high recording frequencies (e.g. 1 min) are usually not available for large urban catchments and detail in spatial data for surface description has to be complemented through on-site observations. Thus, the assessment of LID performance for large urban areas has to overcome these constraints. Previous studies provide suggestions to overcome the lack of flow data for model calibration through parameter regionalization. Recently presented methods for reductions in spatial resolution while maintaining a detailed surface description provide a feasible way to characterize large urban catchments for LID performance assessment. However, rainfall data at high temporal and spatial resolution remains a key element for hydrological model applications in urban areas. We evaluated the impact of spatial and temporal rainfall variability on model performance using the Stormwater Management Model (SWMM) and high-resolution parameterizations of three urban catchments in combination with two rain gauges. While the distance between rain station and catchment did not
affect model parameters we found a reduction in model efficiency with an increasing rain station distance from the catchment.

Keywords: SWMM, high spatial resolution, spatial rainfall variability.

1 Introduction

Land-cover modifications associated with increasing imperviousness alter the hydrological cycle of urbanizing catchments [1, 2]. The resulting environmental impacts on receiving water bodies include higher peak flows and larger runoff volumes, shorter runoff response time, and increased pollutant loads due to washoff from impervious surfaces (e.g. [3–5]). Low Impact development (LID) tools have been developed and applied to mitigate the hydrological effects of urbanization [6]. These tools are designed to maintain or replicate the hydrologic functions of natural catchments, such as evapotranspiration, infiltration, and storage, aiming to mitigate harmful effects at the source areas of runoff and load generation. Typical examples for LID tools are vegetated roofs, permeable pavers, bioretention, and grass swales [6].

Hydrological modelling is one approach to assess the effectiveness of LID tools before their implementation and today a range of suitable models is available [7]. One of them is the Stormwater Management Model (SWMM) [8] which has been successfully applied for LID simulations in small and medium sized catchments [9–11]. However, the assessment for large urban areas remains a challenge [12] as the simulation of small-scale hydrological processes, such as LID tools, requires a high spatial and temporal resolution. Three types of data are required for the parameterization of a hydrological model to a catchment: spatial data describing the surface, subsurface, and drainage network properties of the catchment; flow data for calibration; and meteorological data as model input.

Surface flow in urban areas is affected by obstacles such as street curbs and buildings. Despite the development in the quality of detail of spatial data seen over the past decade [13, 14] typical features of the urban landscape remain often not well presented in available digital elevation models (DEM) [15, 16]. This lack of detail can be complemented by information acquired through on-site observations for small catchments but such field investigations are not feasible for larger urban areas. Thus a reduction in spatial resolution of the model structure is required and results presented by Krebs et al. [17] suggest that lower resolution models developed based on high-resolution models are able to maintain the temporal dynamics of urban runoff.

The fast runoff response times of urban catchments to rainfall require flow data of high temporal resolution (e.g. 1 min.) for model calibration, but such data are usually not available for larger urban catchments [18]. Thus methods for hydrological assessment of ungauged areas have to be developed to compensate the lack of calibration [19] and results presented by Krebs et al. [17] suggest that large urban areas can be parameterized through regionalization of parameters calibrated for smaller high-resolution catchments, where monitoring data are available.
Schilling [20] suggests that a temporal resolution of one minute is needed for rainfall used for hydrological model applications in urban areas. Several studies show that the spatial variability of rainfall is considerable already for small scales [21–23]. Furthermore, spatial rainfall variability has been shown to affect hydrological model parameters and model performance [24–26]. These studies suggest that the spatial rainfall variability should be taken into consideration already for small-scale model applications. However, rainfall data of sufficient spatial and temporal resolution are usually not available for large urban catchments [23, 27].

In this paper we present the effect of spatial rainfall variability on model performance for high-resolution models for three catchments and two rainfall measurement stations of varying distance from the catchments and discuss implications for model applications to a larger urban area.

2 Methodology

2.1 Study site and data

The three study catchments selected for this study are located in the city of Lahti, Finland. Runoff was monitored from 2008-2010 within the STORMWATER program at a one-minute recording interval [28, 29]. The three study catchments vary in size and degree of urbanization: 5.87 ha and an imperviousness of 86% for catchment 1, 6.63 ha and an imperviousness of 54% for catchment 2, and 12.59 ha and an imperviousness of 19% for catchment 3. The typical land-use types are office and apartment blocks in catchment 1, a combination of apartment blocks and detached houses in catchment 2, and sub-urban residential housing in catchment 3 (Fig. 1).

Rainfall data used for model calibration and validation were available from two tipping bucket gages recording at a one-minute interval (AP) and a ten-minute interval (LSB). The rainfall station AP was located at the outlet of catchment 2, where also the flow for this catchment was monitored. The distance between AP and the outlets of the catchments 1 and 3 is 1.0 and 4.9 km, respectively. The LSB station was installed on the roof of the Lahti Science and Business Park located between the catchments 1 and 3. The distance between LSB and the outlets of catchments 1, 2, and 3 is 1.7, 2.7, and 2.3 km, respectively (Fig. 1).

2.2 Model parameterization

The Stormwater Management Model (SWMM) [8] was selected to develop high-resolution parameterizations for the three study catchments. The surface was discretized using surface types and a subdivision into 690 (catchment 1), 784 (catchment 2), and 821 (catchment 3) subcatchments. The subdivision into subcatchments of homogenous surface types rather than land-uses reduces the number of independent calibration parameters [30] and allows the regionalization of parameters to larger areas based on surface properties [17]. The subdivision was based on aerial images from the area and information acquired during on-site
visits. The network data provided by the local water supply company Lahti Aqua was also complemented before applied to the model. In particular, drainage pipes connecting roof gutters to the stormwater network were poorly documented in the dataset. The three models were independently calibrated against selected events from the AP rainfall station and validated against events from the same station and the LSB rainfall station. Further details on parameterization, calibration, and validation are given in [17, 30]. The performance of the calibrated models was thereafter tested with rainfall input data from the different rainfall measurement stations.

3 Results and discussion

The rainfall data from AP and LSB were evaluated to select suitable events for model calibration and validation. Daily accumulations for AP and LSB were first validated against daily rainfall measured by the Finnish Meteorological Institute (FMI) in Lahti-Laune (3.9, 3.3, and 7.4 km from the outlets of the catchments 1, 2, and 3, respectively). This procedure allowed a first assessment of potentially problematic recording periods of AP and LSB due to data gaps and operational
errors. Selected events were then further analysed for the recording time steps through comparison of measured catchment outflow and model simulations with initial parameter values. This comparison indicates whether the temporal dynamics of the measured rainfall event fit the temporal dynamics of the measured catchment runoff, i.e. whether the measured rainfall event was sufficiently similar to the rainfall event generating the measured runoff to be suitable for model calibration and validation. The rainfall depth of events selected events ranged from 2.7–23.7 mm with five minute peak intensities ranging from 0.2-5.8 mm5-1min-1. 12 and 11 events were identified from AP to fulfil the criteria of assessment for the closest catchments 1 (1.0 km) and 2 (0 km), respectively. One event used for catchment 1 could not be used for catchment 2 due to an operational error in the runoff measurement. For the more remote catchment 3 (4.9 km) only 4 events fulfilled the criteria and all other events had to be discarded due to insufficient compliance of measured rainfall and runoff. The assessment of rainfall events from LSB resulted in 5 events for the closest catchment 1 (1.7 km), 8 events for catchment 3 (2.3 km), and 3 events for catchment 2 (2.7 km). While the results for LSB do show a similar pattern concerning the relation between rain station-catchment distances and the number of suitable events as found for AP, the effect is less emphasized which can be explained by the longer recording interval (10 minutes) of this station, which smoothes the temporal rainfall dynamics to some extent (Table 1). These results confirm the spatial variability of rainfall in small scales for high temporal resolution reported in earlier studies [21–23] and indicate that rainfall data recorded at high frequency in close vicinity to the assessed catchment is a requirement when aiming to simulate small-scale hydrological processes in the urban context.

Table 1: Model efficiency $E$, number of events $n$, rainfall recording frequency $T$, and the respective distance $D$ between the rainfall and discharge measurement points.

<table>
<thead>
<tr>
<th>Station</th>
<th>$T$ [min]</th>
<th>$D$ [km]</th>
<th>$n$</th>
<th>$E$</th>
<th>$D$ [km]</th>
<th>$n$</th>
<th>$E$</th>
<th>$D$ [km]</th>
<th>$n$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>1</td>
<td>1.0</td>
<td>6</td>
<td>0.88</td>
<td>0</td>
<td>6</td>
<td>0.97</td>
<td>4.9</td>
<td>3</td>
<td>0.79</td>
</tr>
<tr>
<td>AP</td>
<td>1</td>
<td>1.0</td>
<td>6</td>
<td>0.85</td>
<td>0</td>
<td>5</td>
<td>0.94</td>
<td>4.9</td>
<td>1</td>
<td>0.67</td>
</tr>
<tr>
<td>LSB</td>
<td>10</td>
<td>1.7</td>
<td>5</td>
<td>0.84</td>
<td>2.7</td>
<td>3</td>
<td>0.61</td>
<td>2.3</td>
<td>8</td>
<td>0.81</td>
</tr>
</tbody>
</table>

The independent calibration of the high-resolution models for the three catchments yielded similar parameter values for same surface types present in all catchments (Table 2). This indicates that even though the distance between AP (used for calibration) and the catchments varied, it did not affect the calibrated parameter values. This result is contradictory to findings of earlier studies. Chaubey et al. [25] calibrated the AGNPS model using rainfall data from 17 rainfall stations and found a wide range of calibrated parameter values, depending on the station used for model rainfall input. Andréassian et al. [26] applied three
hydrological models to three different watersheds and concluded that model parameter values are influenced by the quality of rainfall data input. Mohamoud and Prieto [27] found that parameter values of the HSPF model varied with the temporal and spatial rainfall resolution used as model input. A full list of calibrated parameter values for the three catchments is given in Krebs et al. [17].

Table 1: Calibrated parameter values for the individual catchments.

<table>
<thead>
<tr>
<th>Parameter group</th>
<th>Surface</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depression storage $D$ [mm]</td>
<td>Asphalt</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Gravel</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Metal sheet roofs</td>
<td>0.2</td>
<td>0.1</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Lawn</td>
<td>5.0</td>
<td>4.8</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>Vegetation</td>
<td>4.2</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Manning's roughness $n_r$ [-]</td>
<td>Concrete</td>
<td>0.011</td>
<td>0.015</td>
<td>0.015</td>
</tr>
</tbody>
</table>

The performance of the calibrated models was evaluated using the Nash-Sutcliffe efficiency $E$. The best model performance was achieved for the calibration (0.97) and validation (0.94) sequences of catchment 2. Rainfall data for these sequences was measured at AP located at the outlet of this catchment. A clearly lower efficiency was achieved for the validation sequence (0.61) of catchment 2 using data from LSB, located 2.7 km from the outlet of this catchment. A similar pattern can be seen for catchment 1, where the model performance for simulations using AP data was better than for simulations using LSB data. However, the variation in efficiency for catchment 1 was less emphasized than for catchment 2 as the difference in distance between the stations and the outlet of catchment 1 (1.0 km for AP and 1.7 for LSB) is smaller than for catchment 2. The best model performance for the most remote catchment 3 was achieved for the validation sequence using LSB data (0.81) (2.3 km from the outlet of the catchment) while the model yielded lower efficiencies for the sequences using data from AP (4.9 km from the outlet of catchment 3) (Table 1). The simulated and observed flow for the overall best and worst performing rainfall events are shown in Fig. 2. For the event shown in the upper panel (B) the model achieved an efficiency of 0.98. The good temporal synchronization between simulated and observed flow confirms that the rainfall generating the measured runoff was very similar to the measured rainfall event used as model input. For this event both runoff and rainfall data were measured at the same location. For the event shown in the lower panel (A), on the other hand, the achieved model efficiency was only 0.58 and the observed and simulated flow were not as well synchronized. Rainfall data for this event were measured at LSB, 2.7 km from the point where runoff was measured. In this case the rainfall event generating the measured runoff differed from the measured rainfall event both in rainfall depth and its temporal distribution. The event rainfall depths of these events were 10.2 mm (A) and
23.7 mm (B). The rainfall events used for this study covered a wide range of rainfall depths (2.7–23.7 mm). However, a pattern indicating that the influence of spatial rainfall variability on model performance depends on the event size could not be identified. Our results show that the model performance is affected by the distance between the recording rainfall station and the catchment. This indicates that the spatial variability of rainfall affects model performance already at very small scales (< 1 km). Similar results have been reported in earlier studies. Fauré et al. [24] found a drop in the efficiency when spatial variability was neglected for a 4.4 ha catchment. Andréassian et al. [26] reported improved model efficiencies when information on spatial rainfall distribution was used for rainfall model input. In a recent study Mohamoud and Prieto [27] reported higher efficiencies achieved for the HSPF model for rainfall averaged for a network of stations compared to single station rainfall input.

Figure 2: Two rain events simulated for catchment 2 using rainfall data from LSB (A) and AP (B) station.

4 Conclusions

High temporal and spatial model resolutions are needed for the simulation of small-scale hydrological processes, such as LID tools. These model resolutions necessitate that spatial data for model development provides sufficient detail and flow and rainfall data for model calibration is available at a sufficiently high...
temporal and spatial resolution. The availability of such data is a constraint for the hydrological assessment of large urban areas when the aim is to simulate the temporal dynamics of urban runoff. Previous studies provide suggestions to overcome the lack of flow data for the assessment of large ungauged areas through parameter regionalization. Lower model resolutions were shown to sufficiently maintain the model performance while simultaneously providing a detailed surface discretization for the direct access to model parameters for LID tool evaluation.

Rainfall input data with short recording intervals, however, remains a key element for hydrological modelling in the urban context. The results of three catchment parameterizations using SWMM and the evaluation of model efficiency in relation to the distance between the catchment and the rainfall gauge show that the spatial and temporal variability of rainfall is considerable already for small scales. We found a degradation of model efficiency already for a distance of 1 km between the rain gage and the flow monitoring station and a clear degradation in model efficiency for distances around 2.5 km. Thus, information on the spatial and temporal variability of rainfall over the catchment is of major importance for simulations to provide realistic runoff volumes and peak flows for large urban areas.

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References


