Usage of SIMWE model to model urban overland flood: a case study in Oslo

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ABSTRACT

There has been a surge of interest in the field of urban flooding in recent years. However, current stormwater management models are often too complex to apply on a large scale. To fill this gap, we use a physically based and spatially distributed overland flow model, SIMulated Water Erosion (SIMWE). The SIMWE model requires only rainfall intensity, terrain, infiltration, and surface roughness as input. The SIMWE model has great potential for application in real-time flood forecasting. In this study, we use the SIMWE model at two resolutions (20 m and 500 m) for Oslo, and at a high resolution (1 m) at the Grefsen area, which is approximately 1.5 km² in Oslo. The results show that the SIMWE model can generate water depth maps at both coarse and high resolutions. The spatial resolution has strong impacts on the absolute values of water depth and subsequently on the classification of flood risks. The SIMWE model at a higher spatial resolution produces more overland flow and higher estimation of flood risk with low rainfall input, but larger areas of risk with high rainfall input. The Grefsen case study shows that roads act as floodways, where overland flow accumulates and moves fast.

Key words | Nordic cities, Oslo, overland flow, SIMWE, urban flood

INTRODUCTION

Humans are ‘urban species’ nowadays and the urban population is still increasing. Two centuries ago, only 3% of the world’s population lived in cities (Florida 2011). However, the number grew to 34% in 1961 and 55% in 2017 (United Nations Population Division 2018). The global urban population is expected to grow approximately 1.84% per year until 2020 (WHO 2015). By the year 2030, more than five billion people (60% of the global population) will live in urban areas (Florida 2011). In Norway, 82% of the population is living in cities and towns, and more than one million are living in the Oslo urban settlement (SSB 2018a). Meanwhile, the population in Oslo is continuously growing and has increased by 1.2% from 2017 to 2018.

Urbanization has strong impacts on the quantity and quality of local runoff as well as erosion and sediment transport. Urbanization is a process of building more roads, houses, and commercial and industrial buildings (USGS 2018). Subsequently, more wastewater is discharged or leaked into local streams. Roads, buildings, and pavements make the surface impermeable and therefore reduce infiltration. Eventually, urban floods have larger peaks and shorter lag time. Additionally, less infiltration caused by impervious areas leads to declining groundwater recharge, which
reduces baseflow during dry seasons and increases the risk of geological hazards, e.g., land subsidence (Donaldson 1968; Yin et al. 2015).

Urban floods pose a great threat to the security of residents and their properties in inundation areas. In the UK, the estimated expected annual damage caused by flooding in 2002 was approximately one billion British pounds (Hall et al. 2005). In the municipality of Oslo, 2,396 incidents of urban flood-related damage were reported for the period from 2008 to 2014, and the insurance claims reached more than 97 million Norwegian kroner (VAV 2016), which only accounts for approximately 70% of damage events (Finsland, W. 2019, personal communication). In addition to the direct and tangible loss, there are numerous types of indirect and intangible loss. This includes, but is not limited to, the losses from the loss of utilities and supply chain disruption, which is significantly more than the direct cost (NOU 2015).

There are three types of urban floods categorized by cause (Maddox 2014), i.e., coastal (surge flood), fluvial (river flood), and pluvial (surface flood). Coastal and fluvial floods occur in the areas near a coast or along rivers, and the floods take place when the water overflows the barriers. However, in most places, urban floods occur as pluvial flooding, which is due to intensive rainfall that exceeds infiltration rates and drainage capacity of sewage networks. Water may even enter the sewage system in one place and then run out somewhere else and result in flooding.

Climate change, mainly changes in magnitude and frequency of rainfall and snowmelt, makes the issue of urban flooding more complicated. For Norway, annual precipitation has increased by 18% since 1900 and the increasing trend will likely continue (Hanssen-Bauer et al. 2015). The magnitude and frequency of extreme rainfall will also likely increase in the future (Hanssen-Bauer et al. 2015).

Although there is an urgent need to tackle the issue of urban floods, flood risk measurement, modeling, and prediction are still largely inadequate and insufficient, even in developed countries. For the modeling techniques, the MIKE series and Storm Water Management Model (SWMM) are widely used. Both models allow us to estimate water balance components in urban regions and to route flow in pipeline networks. The MIKE series have various models for different purposes, for example, MIKE Hydro for runoff simulation, MIKE Flood for inundation, and MIKE Urban for cities (DHI 2018). Both MIKE Urban and SWMM use a semi-distributed model structure, which means subcatchment is the basic unit for water balance calculation. The drainage network through connecting point to the pipes collects the surface runoff of each subcatchment. However, due to the model limitations, neither model can produce inundation maps nor estimate water depth over a large area. Finally, yet importantly, to set up these two models requires a great deal of manual work.

In this study, we utilize an open-source and physically based spatially distributed overland flow model called SIMulated Water Erosion (SIMWE). The SIMWE model is integrated into a free and open-source GIS platform (GRASS GIS https://grass.osgeo.org/). The SIMWE model can also run from the bash script, which allows us to work on many projects efficiently. The implementation in GRASS GIS also allows us to update input data or model parameters easily. Finally, yet importantly, the SIMWE model inherits high visualizing skills from GRASS GIS, which is important to identify risk areas and design flow paths. The SIMWE model has been used to assess flash floods in the Malá Svinka Basin, Slovakia (Hofierka & Knutová 2015). The results show the gradual changes in water depth across the basin and confirm the excellent robustness and flexibility of the SIMWE model.

The main purpose of this paper is to examine the applicability of the SIMWE model in simulating urban overland flow. We use this model to produce maps of the inundation area and estimate water depth for the whole of Oslo and for a small catchment at a high resolution. Additionally, we test the model sensitivity to spatial resolution and precipitation input. To our knowledge, this is the first time that the SIMWE model has been used for urban flood simulation, and the first time the urban flood simulation for the whole of Oslo municipality has been undertaken. The results are useful for urban flood mitigation and city planning.

**METHODS**

**SIMWE model**

The SIMWE model is a physically based spatially distributed model. The input is net precipitation (rainfall–filtration) and
terrain and surface roughness. The output is water depth, flow velocity, and discharge. In our simulation for urban overland flow, we neglect the sewage drainage system. The stormwater drainage system can reduce the overland flow to some extent. However, drainage pipes become full for extreme rainfall events, for example, 50-year rainfall.

The fundamental theory is the Saint Venant equation for continuity of flow. Urban flood usually occurs as shallow overland flow. For this type of flow, spatial variation in velocity with respect to depth can be neglected (Mitits & Mitasova 1998; Hofierka & Knutová 2015). The flow process can be approximated by the bivariate form of the Saint Venant equation for continuity of flow (Equation (1)):

$$\frac{\partial h(r, t)}{\partial t} = i_v(r, t) - \nabla \cdot q(r, t)$$

(1)

where, $r = (x, y)$ is the position, $t$ is the time, $h(r, t)$ is the depth of overland flow, $i_v(r, t)$ is the rainfall excess = (rainfall – infiltration). $q(r, t)$ is the water flow per unit width.

For a shallow water flow, with the hydraulic radius approximated by the normal flow depth $h(r, t)$, the unit discharge is given by:

$$q(r, t) = v(r, t)h(r, t)$$

(2)

where $v(r, t)$ is the flow velocity. Then, $v(r, t)$ can be derived from Manning’s formula:

$$v(r, t) = \frac{h(r, t)^{\frac{3}{2}}s_f(r, t)^{\frac{1}{2}}}{n(r)}$$

(3)

where $n(r)$ is the dimensionless Manning’s coefficient. $s_f(r, t)$ is the negative gradient of the overland flow surface (hydraulic slope direction):

$$s_f(r, t) = s(r) - \nabla h(r, t)$$

(4)

where, $s(r) = -\nabla z(r)$ is the negative elevation gradient, $z(r)$ is the elevation.

### Classification flood risk levels of urban flood

At present, there is neither an urban flood warning system in Norway nor the criteria for critical urban flood sizes. In this study, we use the height of four different rainboots to classify the urban flood risk levels (Figure 1 and Table 1).

### STUDY AREA AND DATA

**Study area**

Oslo is the capital city of Norway as well as the economic and governmental center. It is one of the northernmost capitals in the world. The city constitutes both a city and a municipality. The urban area extends beyond the boundaries of the municipality into the surrounding municipality, Akershus.

As of 1 January 2018, the municipality of Oslo had a population of 673,469 and the whole population for the urban area reached 1,099,346 (SSB 2018b). The population was increasing at record rates during the early 2000s, making it the fastest-growing major city in Europe at the time. This growth stems from international immigration,

<table>
<thead>
<tr>
<th>Risk level</th>
<th>Low/Green</th>
<th>Challenging/ Yellow</th>
<th>Severe/Orange</th>
<th>Extreme/ Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth</td>
<td>9.5–15.5 cm</td>
<td>15.5–23.5 cm</td>
<td>23.5–43.4 cm</td>
<td>&gt;43.5 cm</td>
</tr>
</tbody>
</table>
high birth rates, and intra-national migration (Wikipedia 2018).

The city is surrounded by a hilly forest and the Oslo Fjord, and they are connected by a number of waterways (Figure 2). The waterways have been subject to a new radical strategy, which has completely reversed the previous approach of enclosing these channels. They are now being actively re-opened in order to make them accessible for people, to efficiently manage stormwater, and to facilitate development and restorations of habitat.

Data

To run the SIMWE model, rainfall, terrain, infiltration, and Manning’s $n$ are required inputs. These data can be spatially distributed or uniform. In this study, we use a spatially uniform rainfall due to the unavailability of spatially distributed rainfall. Other data are spatially distributed.

The terrain data are a hybrid product of two terrain data sets. For the Oslo city area, the terrain map is extracted from LiDAR data operated in the summer of 2014 (BLOM 2014). For the forest and hilly area surrounding the city area, the terrain is interpolated from elevation contours from the Norwegian Mapping Authority. The final terrain product with a spatial resolution of 0.5 m includes the surface area outside the city and the surface area in the city as buildings and roads.

The infiltration map is also a hybrid product of descriptive infiltration capability and impermeable surface (Figure 3). The infiltration capacity is produced from a soil product from the Geological Survey of Norway (NGU 2018). The infiltration capacity is not quantitatively described, but classified into four categories, i.e., none, little, middle, and good. Subsequently, we transform the infiltrate capacity to infiltrate rate according to Table 2. The impermeable surface is from the Sentinel satellite image (Stange 2017) and the Norwegian common (fkb) map database (Norwegian Mapping Authority 2017).
First, the polygons of the infiltrate rate based on NGU and fkb impermeable surface are rasterized into a spatial resolution of 0.5 m. Second, the raster of the Sentinel impermeable surface at a 10-meter grid is resampled by the nearest neighbor to 0.5 m. Lastly, we set the infiltrate rate as 0 mm/h where the surface is impermeable.

Manning’s $n$ value is derived from a landuse map from the Norwegian Institute of Bioeconomy Research (NIBIO 2018). There are six types of land surface identified in Oslo, and a large area of the Oslo city area is classified as ‘built-up’ (Figure 4). The SIMWE model uses Manning’s $n$ to calculate the discharge rate and Manning’s $n$ value for each landuse type is shown in Table 3.
**Experiment design**

Due to the limitation in computer memory and time, for the whole of Oslo, we run the SIMWE model at two selected spatial resolutions and three rainfall events. In total, there are six model runs, as summarized in Table 4.

### Table 2 | Infiltration rate based on a descriptive infiltration capacity and impermeable surface

<table>
<thead>
<tr>
<th>Name</th>
<th>Good</th>
<th>Middle</th>
<th>Little</th>
<th>None/Not classified</th>
<th>Impermeable surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration rate (mm/h)</td>
<td>40</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

There are two sources of impermeable surface, i.e., landuse based on Sentinel satellite and the Norwegian common map database.
The precipitation intensities of 30 mm/h and 50 mm/h are, respectively, at a return period of 10 years and 200 years at the Blindern station. The Blindern station has the longest rainfall measurements in Oslo and is usually used as a reference station in climatology studies. The precipitation intensity of 70 mm/h is the 200 years’ precipitation for the future with climate change. The working flow is summarized in Figure 5.

The model running for the whole of Oslo is used to identify the vulnerable area to flood risk. In addition, we run the SIMWE model at a fine scale, 1 m, at the Grefsen area to examine model behaviors in detail. We select this catchment due to four reasons. First, the sewerage system is relatively simple and there are no pipes to transfer sewage into the catchment. Second, the catchment boundary is well defined. Third, the catchment is relatively steep and flow directions based on terrain are robust. Fourth, the size is good for the model running at a high resolution.

**A case study at Grefsen**

Grefsen is a residential area in the northern part of Oslo (see Figure 6). The case study area is approximately 1.5 km². Most residents live in the eastern part that has a flat terrain. The western part is steep and covered by vegetation. The sewer network is both separated and combined, and

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Manning’s n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Built area</td>
<td>Rough asphalt</td>
<td>0.016</td>
</tr>
<tr>
<td>Agriculture</td>
<td>Mature field crops</td>
<td>0.040</td>
</tr>
<tr>
<td>Forest</td>
<td>Heavy stand of timber, few down trees, little undergrowth, flow below branches</td>
<td>0.100</td>
</tr>
<tr>
<td>Open area</td>
<td>Cleared land with tree stumps, no sprouts</td>
<td>0.040</td>
</tr>
<tr>
<td>Bog</td>
<td>Very weedy reaches, deep pools or floodways with a heavy stand of timber and underbrush</td>
<td>0.100</td>
</tr>
<tr>
<td>Water</td>
<td>Clean, winding, some pools, and shoals</td>
<td>0.040</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Rain 30 mm/h</th>
<th>Rain 50 mm/h</th>
<th>Rain 70 mm/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 m</td>
<td>run500_30</td>
<td>run500_50</td>
<td>run500_70</td>
</tr>
<tr>
<td>20 m</td>
<td>run20_30</td>
<td>run20_50</td>
<td>run20_70</td>
</tr>
</tbody>
</table>

**Table 3** Manning’s n value for each landuse type in the landuse map (Sigstad 2018)

**Table 4** Summary of the model runs for the whole of Oslo

![Figure 5](image-url) | Workflow of this study.
combined sewer overflows occur at the catchment outlet when intensive rainfall events occur. In 2017, combined sewer overflow lasted 5 hours and 23 minutes, and pollution poses a threat to the aquatic life, human health, and groundwater quality in the Akerselva River. Urban hydrological modeling in this catchment is important and meaningful to the water security and environment protection in Oslo.
RESULTS

Inundation area and water depth

The simulated inundation area and water depth are shown in Figure 7. The rainfall intensity is 50 mm/h at the resolution of 500 m. The figure shows that spatially there is much more water accumulated in the Oslo downtown area than the suburban part. The maximum water depth is 0.3 m after a 1-hour rainfall of 50 mm/h. There are four areas experiencing deep inundation, i.e., Skøyen, Oslo center, Alna, and Østensjø. Among these four areas, Østensjø is a reserved wetland, Alna is along the Fossumbekken/Alna River and Loelva, Skøyen is at the outlet area of three rivers into the fjord. This spatial pattern is the same by the model running at 20 m as shown in Figure 8. The overland flow often appears in low and flat areas with high roughness as well as along the rivers. Therefore, we conclude that the SIMWE model can produce the spatial pattern of overland flow and the inundation area is not sensitive to the spatial resolution.

Unlike the spatial pattern of the inundation area, the absolute value of water depth varies due to the spatial resolution. With the same model inputs, the maximum water depth increases from 0.3 m at the 500 m resolution to more than 3 m at the 20 m resolution, although the number of cells with water deeper than 3 m are very few and sparsely distributed. Figure 9 shows the maximum and mean water depth at the two spatial resolutions. With the higher spatial resolution, the mean of water depth increases whereas the maximum of water depth decreases. The effects of spatial resolution on the water depth come from two aspects. The first is that the SIMWE model uses the first-order partial derivatives of the elevation field to calculate water velocity. At a higher resolution, terrain data have higher derivatives and water flows faster than at coarser resolution. Therefore, the mean water depth will be shallower. The second is that higher resolution can preserve local water ponds better than coarser resolution. The maximum water depth at the local sinks is much larger at the spatial resolution of 20 m than at the spatial resolution of 50 m. The effects of spatial resolution exist for all rainfall events in this study and become more noticeable with time.

Classification of urban flood risks

The classification of flood risk is sensitive to the spatial resolution, as shown in Figure 10. With a small rainfall input (30 mm/h), the high resolution model estimates larger areas in risk than by the coarser resolution model. However, with a high rainfall input (70 mm/h), there are smaller areas in risk estimated by the high resolution model than by the coarser resolution model.

There are larger areas classified as low risk flood and smaller areas classified as high risk by the model results at 500 m than the model results at 20 m. In line with flood warning categories, the red warning level (i.e., water depth more than 43.5 cm) only appears in small
areas at 20 m resolution when the rain rate is 70 mm/h, and does not appear at 500 m resolution. The low situation (green warning, water depth between 9.5 and 15.5 cm) appears in all model runs but only appears after 20 minutes’ rain at 500 m.

At 20 m resolution for 70 mm/h rain, the area of the low situation reaches its largest extent after 30 minutes’ rain and decreases afterwards. At the same time, the area of the challenging situation (yellow warning, water depth between 15.5 and 23.5 cm) and the severe situation (orange warning, water depth between 23.5 and 43.5 cm) increases. This means that the water accumulates in some areas and the low situation changes to a challenging situation.

Figure 8 | Map of water depth in the city of Oslo by the model at 20 m with 70 mm/h rainfall (run20_70) at the elapsing time of 1 hour.
A case study at Grefsen

The model results show that roads act as floodways. As shown in Figure 11, both water depth and discharge are high at the side ditches. Additionally, we can find three hotspots in the Grefsen catchment, where there is a relatively large amount of water on the surface. Two of the hotspots are parking lots and one is a football pitch. These three places are relatively low in the surrounding areas and have a low infiltrate rate. To reduce flood risk, first, it is important to keep the floodways open and therefore overland flow can drain quickly. Second, it is possible to make new, or modify, the road networks and other infrastructures to change the flow direction, and consequently to remove the hotspots. Third, it is wise to implement infiltration enhanced nature-based solutions, for example, infiltration trench and bio-retention cells at the location of hotspots.

DISCUSSION

Urban overland flow is usually simulated at a high spatial resolution, from 1 to 5 meters (Hunter et al. 2008; Kulkarni et al. 2014; Chen et al. 2017; Meng et al. 2019) due to the complex urban topography. The high resolution model must be able to present the micro-scale topography and blockage effects. However, such a fine scale cannot be applied to a large area due to the limited computation capacity and time. In this study, we utilize the SIMWE model at two
spatial resolutions, 20 m and 500 m, for the whole of Oslo. The results show that spatial resolution has an impact on the absolute values of water depth and subsequently on the classification of flood risks. However, both spatial resolutions are able to identify the flooding hotspots. This demonstrates that the model results at a coarse resolution can be used to identify flooding hotspots and overflow models with greater detail should be applied in the hotspot areas.

The input data are the main source of uncertainty in urban flood modeling. The input parameters of the SIMWE model are infiltration and surface roughness. They are generated based on maps of impermeable surface and landuse rather than in situ measurements. It is worthwhile to note that the SIMWE model is based on overland flow runoff simulation, which is a simplification of complex hydrological processes in urban areas. For example, the infiltration rate changes with soil moisture content, whereas the SIMWE model uses a constant infiltration rate. In such a case, the SIMWE model is more suitable for event design of extreme precipitation when soil and sewage are already saturated.

**CONCLUSIONS**

Urban flooding is becoming a hot research topic due to the growth of cities and the increase in frequency and magnitude of extreme rainfall events. However, current stormwater management models are too complex to set up and apply on a large scale. In this study, we test a physically based and spatially distributed overland flow model, SIMWE, which is easy to set up and to implement in practice. We drive the SIMWE model at two spatial resolutions with three design rainfall events for the whole of Oslo and at a high spatial resolution at the Grefsen area. The results show that the SIMWE model has high skills in simulating urban overland flood for rainfall events at both coarse and high resolutions. The model at a 20 m spatial resolution estimates a deeper water depth than at a 500 m spatial resolution and this has a strong impact on the classification of flood risks with different rainfall inputs. With a small rainfall input (30 mm/h), there are larger areas in risk estimated by the high resolution model than by the coarse resolution model. However, with a high rainfall...
input (70 mm/h), the high resolution model estimates smaller areas at risk than the coarse resolution model. The case study in the Grefsen area demonstrates that roads are natural floodways. Identification of hotspots provides guidance for implementing flood risk mitigation infrastructure.
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