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Urban hydrological modelling in a developing country with limited data

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Abstract

Accurate hydrological modelling can be challenging in heterogeneous urban catchments, especially in regions with limited data. SWMM configurations were set up for two urban catchments in South Africa to test the performance of this model for urban areas in developing countries. Despite the relatively small catchment sizes, inconsistencies are evident between observed rainfall and measured runoff for most events. Model scenarios were created with various sets of parameter values, first from literature and then from values physically measured in the catchments. The observed and simulated flow comparisons were improved by incorporating model parameter values derived for this study, although the results were inconsistent. As the region experiences storms with considerable spatial distribution, the flow gauging stations sometimes record runoff which does not correspond to an observed rainfall event with corresponding intensity, and vice versa. Recommendations are made for further improvement of the modelled results using radar data for significant rainfall events and incorporating storage areas throughout the catchments to simulate unintended attenuation.

Highlights

- Hydrological modelling is challenging in regions with limited observed data.
- An attempt is made to improve results using site-specific imperviousness and connectivity.
- Despite some improvement, results remain inconsistent and future work is proposed.

Introduction

Hydrological modelling of heterogeneous urban catchments presents numerous challenges. Although the influence of impervious surfaces on runoff is widely understood and accepted, the impact of pervious areas within the urban environment is still not fully understood (Braud *et al.*, 2013; Fletcher *et al.*, 2013; McGrane, 2016). Heterogeneous urban catchments have a combination of fast and slow hydrologic responses, resulting from considerably different flow paths, mainly caused by the interaction between natural portions of the catchment and sections dominated by engineered drainage, for example, by pipe flow (Braud *et al.*, 2013).

Like many developing countries, South Africa has a wide range of urban development types. Some land cover classes tend to have higher percentages of total impervious areas (Loots *et al.*, 2025) and more impervious areas that are directly connected to natural or engineered drainage systems than others (Loots *et al.*, 2025b). Additionally, urban areas in the interior are subject to convective storms with high spatial variability. These characteristics need to be considered in hydrological modelling of South African urban areas. This requires the use of a hydrological model with the ability to model catchment

heterogeneity as well as routing through the catchment. The Storm Water Management Model (SWMM) is one of the most widely used storm water models both internationally (Elliot and Trowsdale, 2007; Fletcher *et al.*, 2013; Arjenaki *et al.*, 2021; Dell *et al.*, 2021; Zeng *et al.*, 2021) and in SA (City of Cape Town Development Service, 2002; Barnard *et al.*, 2019).

The aim of this study was to assess if the incorporation of urban landcover and impervious area connectivity characteristics determined specifically for South Africa improves hydrological modelling in areas with heterogeneous development.

Methodology

Study areas

Two gauged urban catchment areas in Tshwane, South Africa, with comparable sizes and similar combinations of land uses, were used for this study (Figure 1a). The first catchment was used to evaluate parameter value sets and the second catchment was used to validate the use of the chosen parameter values. The two catchments were chosen based on their relatively small areas (30 km² and 35 km²), relatively homogeneous land use (Figure 1b) (Geoterraimage, 2021) and the location of rain gauges with more than 20 years of 5-minute interval rainfall data in the vicinity (Figure 1a). High-resolution soil information from the SCS Terrain Unit (TU) map by Schulze and Schütte (2023) (Figure 1c) was used.

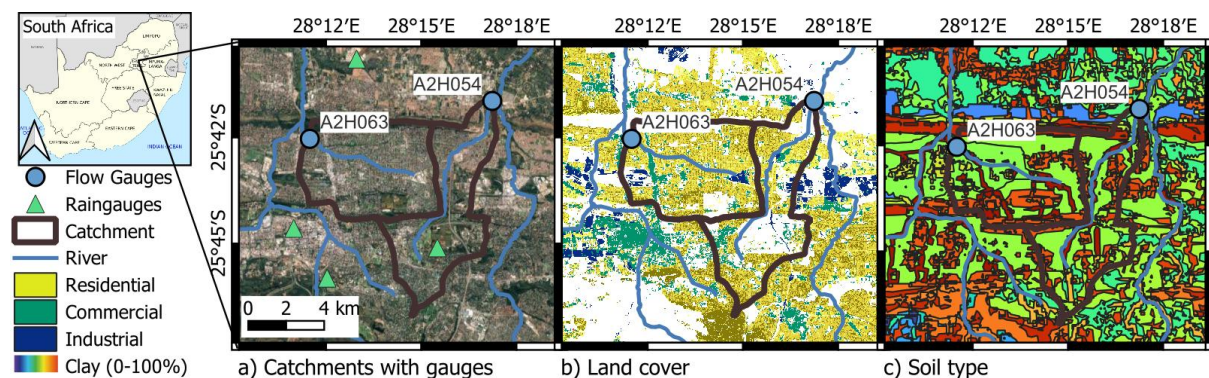


Figure 1. Study catchments with (a) satellite imagery, (b) land cover and (c) soil data

Model configuration and validation

The SWMM model was configured with 263 sub-catchments for A2H063 and 146 for A2H054, based on the land cover classifications (Figure 1b). Sub-catchment areas with similar land cover characteristics, as well as small land parcels like trees lining roads, were incorporated into larger sub-catchments. Soils data was added based on the dominant SCS Terrain Unit (Figure 1c) in each sub-catchment. Due to the number of sub-catchments in the two configurations, it was not practical to model each stormwater drain as obtained from the Tshwane as-built drainage drawings. Only drainage pipes downstream of entire sub-catchments were included in the configuration. Streams and rivers were added based on satellite imagery. Inlets to the drainage system were modelled as junctions.

Representative catchment rainfall was generated with infilled rainfall records from the closest rainfall stations, using Thiessen polygons to allocate gauges to sub-catchments. A continuous simulation model was run with 5-minutes time-step rainfall to better simulate antecedent soil moisture conditions and the short durations of flood events in each catchment.

As the SWMM has the ability to incorporate catchment attributes such as the Total Impervious Areas (TIA) of a sub-catchment, as well as impervious areas that are directly connected to drainage systems, or Directly Connected Impervious Areas (DCIA), two alternative approaches are generally followed to derive CN values for modelling (Rossman and Huber, 2016).

In the first approach, overall urban CN values that incorporate TIA and DCIA are assigned to sub-catchments, with TIA in the SWMM set to zero. For sub-catchments with impervious areas that are directly connected to drainage systems, or areas with more than 30% TIA, the USDA (2004) proposes using Equation 1 to derive a composite CN:

$$CN_C = CN_P + \frac{TIA_{\%}}{100} (98 - CN_P) \quad (1)$$

where

CN_C = composite Curve Number,
 CN_P = pervious Curve Number, and
 $TIA_{\%}$ = total impervious area (%).

For catchments with impervious areas that are unconnected from drainage systems, or less than 30% TIA, the USDA (2004) proposes using Equation 2:

$$CN_C = CN_P + \frac{TIA_{\%}}{100} (98 - CN_P)(1 - 0.5R) \quad (2)$$

where

CN_C = composite Curve Number,
 CN_P = pervious Curve Number,
 $TIA_{\%}$ = total impervious area (%), and
 R = ratio of unconnected impervious area to total impervious area

In the second approach natural CN values are applied, with TIA and DCIA added separately in the SWMM (Rossman and Huber, 2016). The SWMM accommodates directly connected versus Unconnected Impervious Areas (UIA) by routing the unconnected portion of the runoff generated on impervious areas over pervious areas before reaching the sub-catchment outlet. The remainder of the runoff is routed directly to the outlet as DCIA. The input parameter for the SWMM is therefore the proportion of TIA that is not connected to drainage systems, with the subarea routing set to *Pervious*. It should be noted that $DCIA_{\%}$ is reported as a proportion of the total sub-catchment area.

The model was initially run using two alternative approaches described in the preceding paragraphs, with parameter values as found in the literature. After the initial model runs were completed, the model was run twice more, with Parameter Set (PS) values as derived by (Loots *et al.*, 2025) and (Loots *et al.*, 2025b). For the first model runs, two conventional parameter sets were evaluated:

PS (A) Composite urban CN values were derived with 0% TIA and flow routed directly to sub-catchment outlets. CN values were derived as proposed by the USDA (2004), with Equation 1 used for areas with 30% or more TIA and Equation 2 for areas with less than 30% TIA, based on the assumption that areas with less than 30% TIA would generally be unconnected from drainage systems (USDA, 2004). CN_P values for all residential, commercial and industrial areas were set to model pasture in good hydrologic condition (USDA, 2004). TIA for urban land cover as required for Equations 1 and 2 was estimated based on the imperviousness proposed by Schulze *et al.* (2004).

PS (B) CN values for natural land cover were applied with TIA for urban land cover estimated based on the imperviousness proposed by Schulze *et al.* (2004). DCIA was estimated based on the assumption made by the USDA (2004) that areas with less than 30% TIA are unconnected, and areas with 30% or more TIA are connected to drainage systems.

Next, the knowledge gained in (Loots *et al.*, 2025) and (Loots *et al.*, 2025b) was used to create two additional parameter sets in order to evaluate whether the derived values would improve results:

PS (C) Composite urban CN values were derived with 0% TIA and flow routed directly to sub-catchment outlets. CN values were derived as proposed by the USDA (2004), with Equation 1 used for areas with 30% or more TIA and Equation 2 for areas with less than 30% TIA, based on the assumption that areas with less than 30% TIA would generally be unconnected from drainage systems (USDA, 2004). CN_p values for all residential, commercial and industrial areas were set to model pasture in good hydrologic condition (USDA, 2004). TIA for urban land cover as required for Equations 1 and 2 was estimated based on the parameter values proposed in (Loots *et al.*, 2025) for different SANLC classes.

PS (D) CN values for natural land cover were applied with TIA for urban land cover estimated based on the imperviousness proposed in (Loots *et al.*, 2025). DCIA values were applied as derived in (Loots *et al.*, 2025b).

The performance of each PS was assessed considering comparison between observed and simulated maximum flow rates, mean flow rates and the total flow volumes. The Root Mean Square Errors (RMSE) and Coefficients of Determination (R^2) were also evaluated.

Results and discussion

Disparity was observed between the observed rainfall and runoff data, as shown in Figure 2a for Catchment A2H063. Figure 2b shows a scatter graph of the observed and simulated flow hydrographs for the study period between 1994 and 2022 for the SWMM model configuration of Catchment A2H063 with PS A as an example of the difference between simulated and observed runoff. The model with PS A, PS B, PS C and PS D all overestimated flow rates for numerous events, but for some events the simulated runoff was significantly lower than observed flow. The data was checked for phasing and total volume simulated. No phasing issues were evident. The region experiences storms with considerable spatial variation (Dyson, 2009), so it is possible that the flow gauging station might sometimes register runoff from rainfall events for which the representative catchment intensity is not recorded at the rainfall stations, and vice versa.

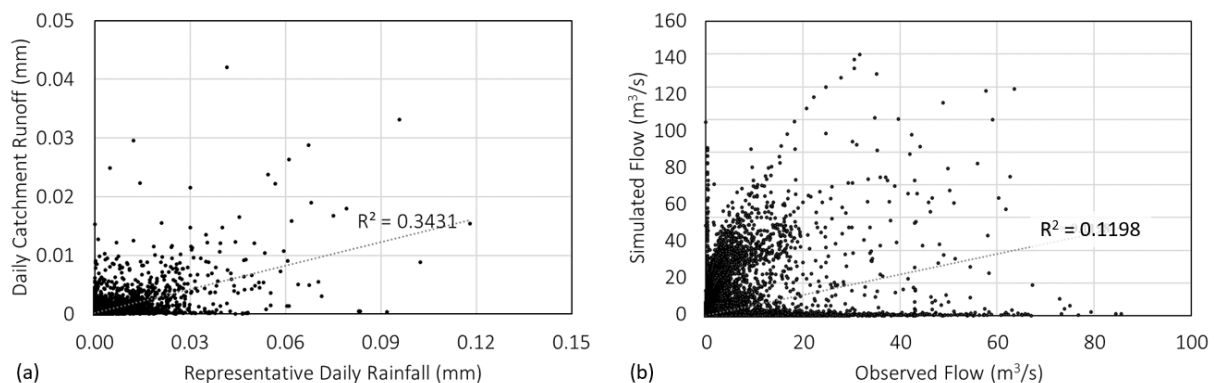


Figure 2. Scatter plots of (a) representative daily rainfall depth and daily catchment runoff, both reported in mm; (b) SWMM results versus observed flow for Catchment A2H063 for the period from 1994 to 2022: PS-A

The results of the four simulation scenarios run for A2H063 are summarised in Table 1 and for A2H054 in Table 2. As shown in these tables, the results are not consistent across objectives. For example, PS A has the most realistic maximum flow for A2H063, but the lowest R^2 value. PS D has a maximum flow rate more than 43% higher than the observed maximum, but it modelled the mean flow and total volume the best. PS B overestimated the mean flow and total flow volume by more than 68% for A2H063 and by over 26% for A2H054, but had the best R^2 values and RMSE for both configurations. Furthermore, all the simulations overestimated the maximum flow rate for A2H063, but underestimated the maximum flow rate for A2H054. The R^2 values are generally low and the RMSE values, high. It is possible that the low R^2 value and high RMSE are due to the significant spatial distribution of rainfall in the study area (Makgopa, 2015; Mouton *et al.*, 2025) and low rain gauge

density. It is also possible that other factors influence the runoff from South African urban catchments, that have not been quantified in the model. This warrants further investigation.

Table 1. Summary of SWMM results for A2H063 (with red, orange, yellow and green showing results from worst to best for each objective)

| Data Set | Max Flow (m ³ /s) | Mean Flow (m ³ /s) | Total Volume (Mm ³) | R ² | RMSE |
|----------|------------------------------|-------------------------------|---------------------------------|----------------|------|
| Observed | 91.4 | 0.181 | 160.7 | | |
| PS A | 104.3 | 0.170 | 149.8 | 0.120 | 164 |
| PS B | 130.8 | 0.305 | 269.1 | 0.471 | 151 |
| PS C | 117.0 | 0.160 | 141.3 | 0.267 | 183 |
| PS D | 131.1 | 0.191 | 168.0 | 0.356 | 189 |

Table 2. Summary of SWMM results for A2H054 (with red, orange, yellow and green showing results from worst to best for each objective)

| Data Set | Max Flow (m ³ /s) | Mean Flow (m ³ /s) | Total Volume (Mm ³) | R ² | RMSE |
|----------|------------------------------|-------------------------------|---------------------------------|----------------|------|
| Observed | 96.1 | 0.165 | 145.9 | | |
| PS A | 92.0 | 0.189 | 167.0 | 0.421 | 169 |
| PS B | 94.1 | 0.209 | 184.5 | 0.413 | 142 |
| PS C | 91.5 | 0.178 | 157.3 | 0.413 | 146 |
| PS D | 90.9 | 0.189 | 167.5 | 0.395 | 153 |

Conclusions and future work

The aim of this study was to assess if the incorporation of urban landcover characteristics determined specifically for South Africa improves hydrological modelling in areas with spatially varied development typical of the region. The incorporation of imperviousness and impervious area connectivity values derived for the study areas improved certain results, although the final results showed inconsistency between different result objectives and between catchments.

Despite the relatively small catchment sizes, disparity exists between observed rainfall and measured runoff for certain events. As none of the rain gauges are situated inside the catchment area and the region experiences storms with considerable spatial distribution, it is possible that the flow gauging station might sometimes register runoff from rainfall events for which the representative catchment intensity is not recorded at the rainfall stations, and vice versa. This would need to be further investigated using radar data and analysis of significant rainfall-runoff events to isolate this issue.

It has previously been postulated that unexpected attenuation is prevalent in the study catchments (Loots *et al.*, 2023). Therefore, it is also recommended that typical storage potential be quantified for properties with formal urban land cover in South Africa and incorporated in an improved model configuration. It is recommended that the parameter values used in this study be tested on additional gauged catchments, particularly catchments with informal development, to determine whether the results are applicable to all ungauged catchments in the region.

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