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Novel methodology for development of city scale hydrological-hydraulic models: from subcatchment delineation to calibration

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Abstract

The study proposes a novel six-step methodology for the development of a city scale hydrological-hydraulic models with adequate spatial resolution. In an era of almost unlimited data, the key challenge is the selection of appropriate data sources and the rational use of data for time efficiency. The novel methodology uses the socio-economic sectors of the city of Girona and a simplified version of the Copernicus urban atlas data to create subcatchments of homogeneous land use type and similar sizes. Network topological consistency was conducted using a novel Python algorithm, based on graph theory. Flow routing from the catchments to the network considers terrain slope and maximum flow path distance. The result exhibits a spatial resolution capable of considering land use properties, while also avoiding a very high spatial resolution, to prevent complexities in the calibration process. The methodology was applied to Girona, Spain, resulting in 351 subcatchments. Preliminary results indicate that this semi-automated approach effectively balances spatial resolution and computational efficiency, providing a robust framework for urban hydrological-hydraulic modelling. Ongoing calibration efforts aim to further refine the model.

Highlights

- Simplified methodology for delineating subcatchments considering land use homogeneity.
- Network topological consistency using a graph theory approach.
- City scale EPA-SWMM model calibration using NSGA-II.

Introduction

Climate change and urbanization intensify urban flooding and water pollution Urban drainage has been historically designed with linear and end-of-pipe solutions. The increasing volume of combined sewer overflows (CSOs), even as a small proportion of the total annual wastewater discharge, contributes to 30–95% of the annual load for different pollutants (Botturi et al., 2021). To face this scenario, communities should adapt, moving away from only conventional drainage methods and use Sustainable Urban Drainage Solutions (SUDS), solutions that mimic natural water cycle, controlling flood while also improving runoff water quality. Hydrological-hydraulic models can be used for the evaluation of catchment runoff, assessment of SUDS flow effects and quantification of their benefits (Rossman et al., 2016). However, developing city-scale hydrological-hydraulic models is expensive, time-consuming and requires significant amounts of input data.

Therefore, our approach aims to provide an alternative methodology for subcatchment delineation with a 'just enough' spatial resolution - sufficient to produce subcatchments with relatively homogeneous land use - while maintaining a semi-automated process and avoiding excessive computational burden during hydrological-hydraulic model execution.

The main goal of this work was to develop a simplified methodology, open source-based, to build a hydrological-hydraulic model with adequate spatial resolution, capable to integrate both criteria: land use homogeneity and low computational effort for calibration. The key principles considered in the model include:

- **(i)** Graph theory for topological consistency of the network
- **(ii)** Creating homogeneous subcatchments based on land use type.
- **(iii)** Flow routing assumes the direction determined by the existence of a minimal surface level difference and maximum flow path distance from catchment areas to the network nodes.
- **(iv)** Accounting for baseline conditions of surface hydrology inside the catchments by considering flow routing between pervious and impervious areas within subcatchments. The methodology was developed and applied to the city of Girona, Spain.

Methodology

The model setup uses three software packages, SWMM (Storm Water Management Model), Python, and a free plugin dedicated to the integral management of the water cycle (GISWATER). The latter communicates SWMM to a spatial database using the QGIS interface. To establish the hydraulic and hydrological input characteristics of the combined sewer system (CSS), it was first necessary to collect the network inventory and spatial and temporal data from public domain sources. These activities were followed by six steps, which are illustrated in Figure 1 and are described in more detail below.

Step 1 – Catchment delineation: To create homogeneous units with spatially averaged descriptive features, sub-basin delineations were relied on the Copernicus (2018) land use urban atlas data. This layer was reclassified, considering the previous land use types into only two types of land use, pervious and impervious. This layer was intersected with the socioeconomic districts of the city. This geoprocessing process is intended to generate subcatchments of uniform size, shape, and homogeneous land use. Those characteristics provide greater accuracy when obtaining the mean hydrological properties, while low discrepancies in subcatchment sizes favour model continuity (Lee at al., 2018). A total of 351 subcatchments were obtained for the entire urban area and the agriculture zones of the city.

Step 2 – Network topological consistency: A graph-based Python algorithm iteratively corrects arc directions until the network is fully connected and oriented. Key graph theory concepts applied include network connectivity, ensuring all nodes are connected to the Wastewater Treatment Plant (WWTP) or an overflow outfall. The first step in achieving network consistency is directional adjustment, aligning arcs to ensure proper flow paths. Next, elevation adjustments resolve missing or unrealistic values using Digital Terrain Model (DTM) data, maintaining logical elevation gradients. Slope adjustments prevent stagnation and ensure proper hydraulic behaviour, constraining slopes within an acceptable range (ϵ < slope < 8); negative slopes are corrected by averaging node elevations, with adjustments propagating iteratively.

Steps 3 & 4 – Flow routing from the subcatchments to the network and determination of surface properties: Each subcatchment was connected to the outlet (network nodes) using a QGIS plugin called *buildings2sewer* developed by ICRA. The use of this plugin enables the subcatchments to be connected to the closest node considering surface elevation criteria and distance. The altitude tolerance was set as 2 meters, and the maximum distance 40 meters (due to the medium distance calculated between the nodes of the CSS). Afterwards, geoprocessing tools were used to calculate mean values for imperviousness and slope based on satellite data (DEM).

Step 5 – Assumptions on flow routing within the subcatchment: The subcatchments are directly connected to the network, making no distinction between directly or indirectly connected impervious areas. Within the interface of QGIS, using GISWATER, we define routing conditions within each subcatchment. Based on previous basins' classifications (Lee et al., 2018), the routing condition implies three types of subcatchment composition. (Figure 1, Step 5):

- ***I.*** Stand Alone Pervious Area (SA-PA): for subcatchments landscape 100% perviousness.
- ***II.*** Subcatchment with both pervious and impervious area: where pervious area functions as a Buffer Pervious Area (BPA), receiving flow from Indirected Connected Impervious Area (ICIA) and the impervious area directly connected to the outlet (DCIA).
- ***III.*** Stand Alone Directed Connect Impervious Area (SA-DCIA): representing landscapes, such as the buildings and streets.

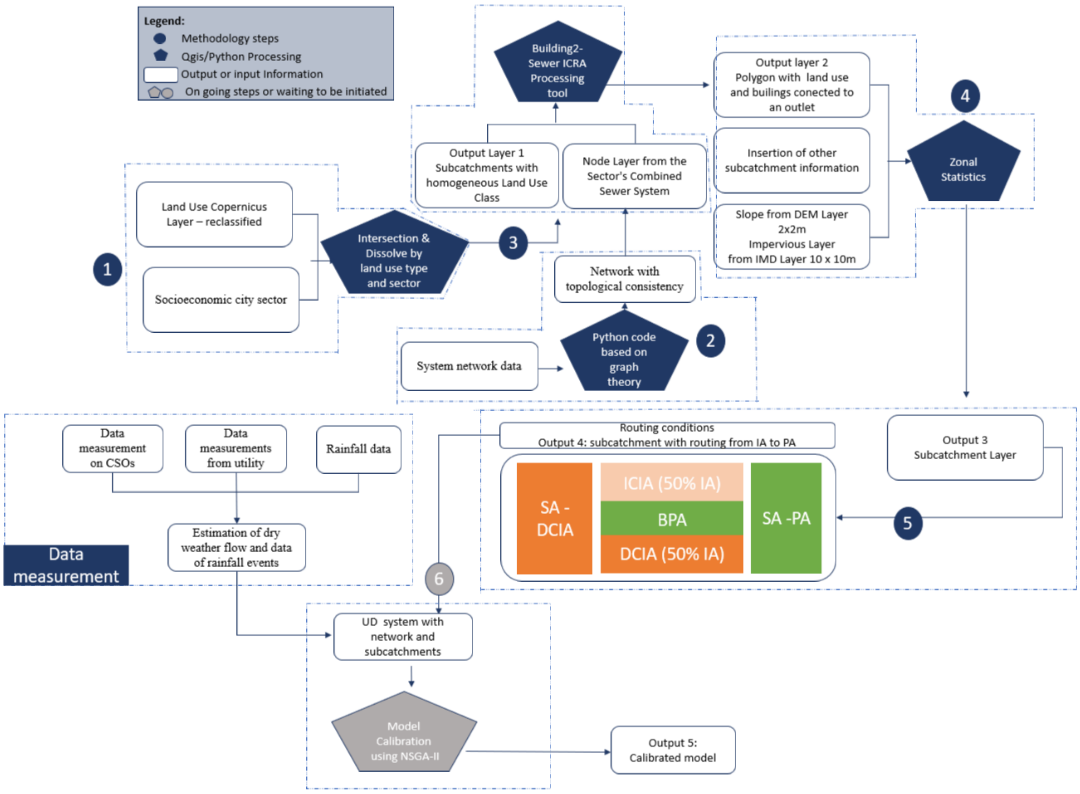

Figure 1. A novel six-step methodology for the development of city scale hydrological-hydraulic models.

Step 6 – *Model Calibration*: Once topological consistency is established, hydraulic-hydrological calibration follows, using CSO monitoring and dry weather flow data collected from different points of the network. Calibration of the SWMM model against measured flow is performed using the Non-Dominated Sorting Genetic Algorithm (NSGA-II). The calibrated parameters with respect to subcatchment flow are %Imperv, N-Imperv, N-Perv, S-Imperv, S-perv, and hydraulic path of surface runoff; with respect to pipe flow, pipe roughness is calibrated. The calibration process uses the Nash–Sutcliffe Efficiency coefficient as an indicator to assess the quality of the calibration, by comparing the measured and simulated data. This step adjusts model parameters to align simulated water volumes and flow dynamics with real-world measurements.

Results and discussion

The implementation of the first five steps of proposed methodology resulted in a development of a city scale hydrological-hydraulic model of the city of Girona, Spain. The 351 subcatchments obtained are shown in Figure 2. The figure indicates which type of the two internal flow routing options within the subcatchment (pervious or impervious) is used. Step number 6, calibration of the whole city model is still in process, due to ongoing flow measurements.

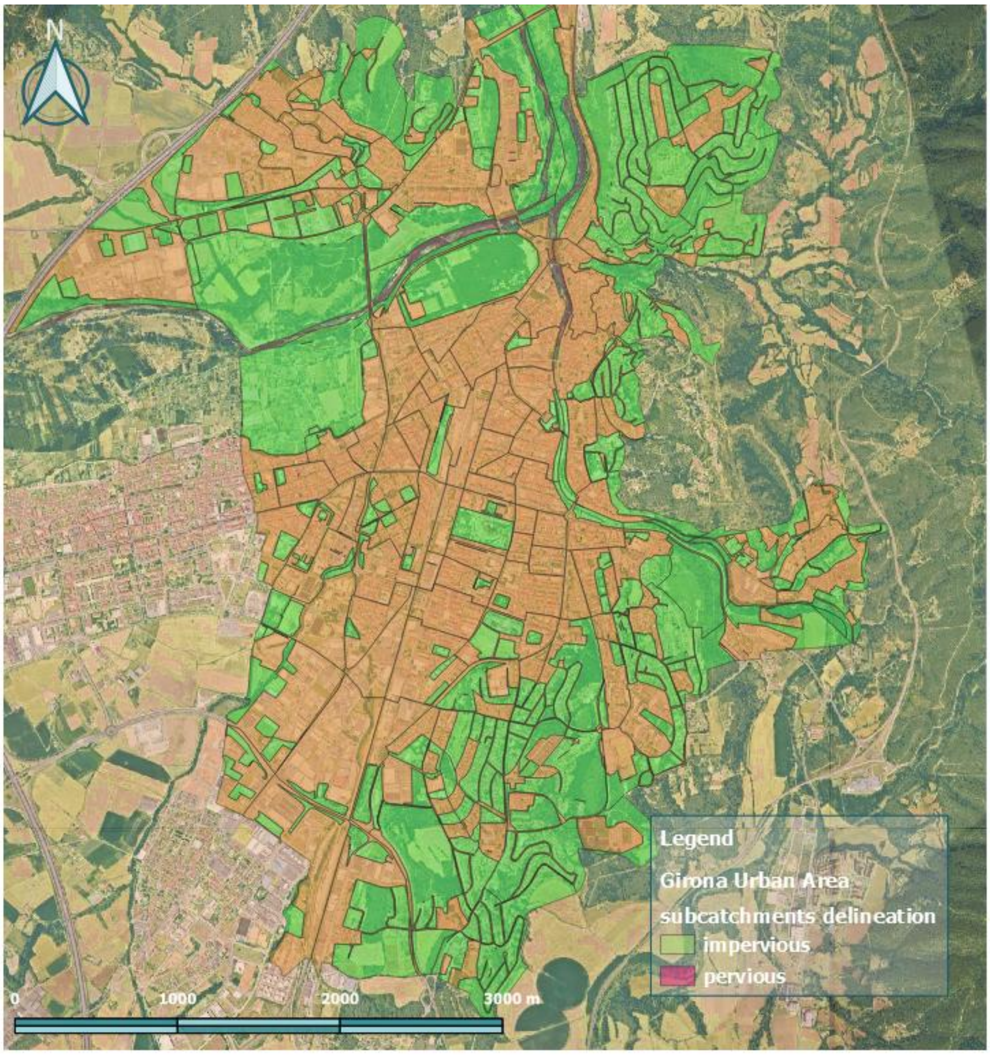

Figure 2. Six steps needed for the model development.

Conclusions and future work

The preliminary results show that the proposed methodology enables efficient development of a city scale hydrological-hydraulic model. Namely, open-source data was used for delineation and determination of subcatchment properties. The ongoing flow measurements and model calibration using NSGA-II will deliver a calibrated city scale model.

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