SuDS at the Street-scale: Aggregation Modelling Methods

Les systèmes de drainage durable à l'échelle de la rue : méthodes de modélisation par agrégation

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RÉSUMÉ

Les systèmes de drainage durables (SuDS) sont de plus en plus utilisés pour atténuer les inondations, améliorer la qualité de l'eau et restaurer la fonction hydrologique urbaine, mais dans la réalité, les rénovations se font généralement à petite échelle et de manière fragmentée. L'évaluation des performances combinées des SuDS à l'échelle de la rue nécessite souvent une modélisation hydraulique détaillée, qui peut être très gourmande en ressources informatiques. Cette étude évalue deux stratégies d'agrégation : *LumpN*, qui regroupe les SuDS par type, et *LumpOne*, qui représente tous les SuDS comme un seul système composite, par rapport à une base de référence entièrement désagrégée à l'aide d'un cadre de modélisation hydrologique 1D basé sur les concepts SWMM LID. Une approche Monte Carlo a généré 500 bassins versants synthétiques à l'échelle de la rue contenant différentes configurations de toits verts et de systèmes de biorétention. Des précipitations continues provenant d'une année hydrologique complète ont été appliquées afin de comparer les prévisions de ruissellement entre les différentes stratégies d'agrégation. Les résultats indiquent que *LumpN* préserve le comportement hydrologique avec une grande précision, obtenant des valeurs d'efficacité Nash-Sutcliffe élevées et des estimations raisonnables du débit et du volume de pointe. En revanche, *LumpOne* introduit des erreurs substantielles, en particulier dans les systèmes comportant des types de SuDS mixtes ou des caractéristiques physiques hétérogènes, principalement en raison d'une surestimation de l'exfiltration dans la représentation agrégée. Les résultats montrent que l'agrégation basée sur le type offre une alternative fiable et efficace sur le plan informatique à la modélisation entièrement détaillée, tandis que l'agrégation complète doit être appliquée avec prudence lorsque la diversité des SuDS modélisés est élevée.

ABSTRACT

Sustainable Drainage Systems (SuDS) are increasingly being implemented to mitigate flooding, improve water quality, and restore urban hydrological function, yet real-world retrofits typically occur at small, fragmented scales. Assessing the combined performance of SuDS at the street scale requires detailed hydraulic modelling, which can be computationally intensive. This study evaluates two aggregation strategies—*LumpN*, which groups SuDS by type, and *LumpOne*, which represents all SuDS as a single composite system—against a fully disaggregated baseline using a 1D hydrological modelling framework based on SWMM LID concepts. A Monte Carlo approach generated 500 synthetic street-scale catchments containing varying configurations of green roofs and bioretention systems. Continuous rainfall from a full year was applied to compare outflow predictions across aggregation strategies. Results indicate that *LumpN* preserves hydrological behaviour with high accuracy, achieving strong Nash–Sutcliffe Efficiency values and reasonable peak flow and volume estimates. In contrast, *LumpOne* introduces substantial errors, particularly in systems with mixed SuDS types or heterogeneous physical characteristics, largely due to overestimated exfiltration in the aggregated representation. The findings show that type-based aggregation offers a computationally efficient yet reliable alternative to fully detailed modelling, while full aggregation should be applied cautiously when the diversity of the modelled SuDS is high.

KEYWORDS

Aggregation, Modelling, Stormwater Management, Street-Scale, Sustainable Drainage Systems

1 INTRODUCTION

Sustainable Drainage Systems (SuDS) are widely promoted to mitigate flood risk, enhance water quality and restore urban hydrological function (Woods-Ballard et al., 2015). In practice, SuDS retrofits occur opportunistically and typically at small scales, resulting in distributed and highly heterogeneous configurations. At the street-scale, assessing the combined hydrological impact of these fragmented installations is essential, yet full-detail hydraulic modelling of each SuDS unit (using SWMM or similar modelling tools) is time consuming and computationally costly. Consequently, this has led to interest in aggregated modelling approaches where multiple SuDS are represented as a single equivalent unit. Whilst aggregation can reduce the computational burden, it introduces simplifications that may distort key processes such as exfiltration, detention and overflow. Examples of successful SuDS aggregation strategies in the literature are limited. Elliott et al. (2009) progressively reduced model resolution from 810 SuDS units to a single aggregated device in MUSIC, highlighting reduced computational load combined with only a minor loss in accuracy. Similarly, Roldin et al. (2012) used MIKE URBAN to evaluate a soakaway aggregation strategy, reporting only small discrepancies in peak flow and volume compared with detailed models. However, both studies focused on single SuDS types (e.g., infiltration devices only), rather than the aggregation of multiple, more diverse, SuDS types commonly seen in practice.

The motivation for this study is to evaluate the hydrological accuracy of modelled SuDS performance under different aggregation strategies at the street-scale. The specific objectives of this study are as follows: i) To develop modelling frameworks for aggregating SuDS both within the same type (e.g., multiple bioretention units with varying configurations) and across different types (e.g., green roofs, bioretention cells); ii) To define a set of representative SuDS types and associated configuration parameter ranges, and to conduct Monte Carlo simulations to examine the model accuracy under continuous rainfall conditions at the street scale; iii) To analyse the sensitivity of model performance to key factors across different modelling strategies.

2 METHODOLOGY

A 1D hydrological model was implemented in MATLAB (R2023a), based on the widely used and validated SWMM LID conceptual model framework (Rossman, 2016), which enables the simulation of the hydrological and hydraulic dynamic of SuDS. The model enabled simulation of both single SuDS units and aggregated systems, providing a unified structure for testing different aggregation strategies.

Two aggregation strategies, *LumpN* and *LumpOne,* were evaluated against a fully disaggregated baseline scenario (referred to as *Detailed*). In the *Detailed* method each SuDS unit is explicitly assigned to a single subcatchment with user-defined spatial coverage and configuration. In *LumpN*, *N* different types of SuDS are modelled separately, whereas in *LumpOne*, all SuDS are aggregated into one single device. Figure 1 presents the conceptual frameworks for these strategies. The *LumpN* method aggregates multiple small, non-homogeneous subcatchments into a larger catchment, grouping SuDS by type. For instance, all catchments served by green roofs are consolidated into a single, larger unit receiving the combined inflows from individual subcatchments. This approach can also accommodate further subdivisions based on specific design attributes, such as distinguishing between lined and unlined bioretention configurations. The *LumpOne* method builds on the *LumpN* approach by aggregating all subcatchments and SuDS into a single composite SuDS system.

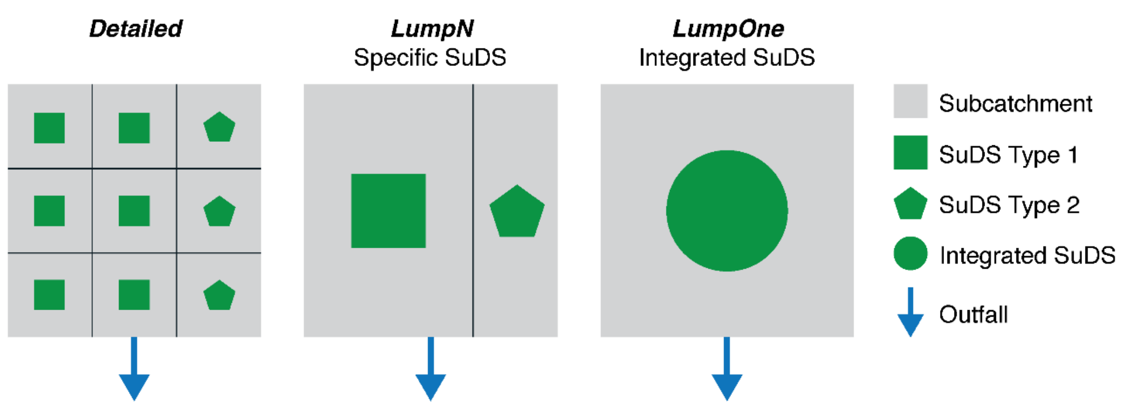

Figure 1. Conceptual framework of the disaggregated baseline scenario (*Detailed*) and the two aggregation strategies (*LumpN* and *LumpOne*).

To represent the variability in SuDS physical configuration parameters, a Monte Carlo simulation approach was adopted. 500 synthetic street-scale catchments (5000 m²) were generated. Each synthetic catchment contained 10 to 20 SuDS units whose type (green roof, GR, or bioretention, BIO), treatment area and physical parameters (e.g., soil depth, saturated hydraulic conductivity, storage depth) were randomly sampled from uniform distributions of literature sourced ranges. GR units were configured such that the physical area was always equal to the runoff treatment area. In contrast, each BIO unit was designed to manage a contributing drainage area larger than its plan area. BIO units were designed to satisfy: i) no overflow under a 30-year design storm; and ii) Greenfield runoff rate constraints (3 L/s/ha). Unlike GR, where exfiltration is not permitted, BIO systems could be lined or unlined with equal probability.

An area weighted mean parameter estimation method was used to estimate the aggregated model parameters for the *LumpN* and *LumpOne* methods. For orifice-controlled outflows in BIO, the aggregated orifice size of each BIO unit was calculated based on the Greenfield Runoff Rate, corresponding catchment area and total BIO depth. This approach maintained the peak outflow of the aggregated SuDS but may not have robustly represented other stages of the head-discharge relationship. A full year (2007) of 5-minute rainfall from Sheffield (UK) was applied to each synthetic catchment (Stovin, 2024). The rainfall timeseries included several significant rainfall events. Monthly potential evapotranspiration data based on long-term climate averages for Sheffield were taken from Stovin et al. (2013). Performance of the aggregation strategies in comparison to the disaggregated baseline was evaluated on an annual and per-event basis. Three performance metrics were evaluated: i) Nash-Sutcliffe Efficiency (NSE) of continuous outflow predictions; ii) Peak outflow error (%) for a significant event; and iii) Annual outflow volume error (%).

3 RESULTS

Simulation setup, output and aggregation strategy performance metrics for an example case are presented in Figure 2. Figure 2a, presents the range of physical characteristics observed over the 19 SuDS of this scenario (Figure 2b). Figure 2a demonstrates that whilst the weighted mean of some parameters in the *LumpOne* strategy (COM) closely resembled those of the *LumpN* strategy (GR and BIO for Porosity and Wilting Point), others exhibited significant differences (e.g Ponding Depth and Exfiltration Rate). These discrepancies resulted in poor performance of the *LumpOne* method, both during significant rainfall events (Figure 2d) and over the full annual timeseries (Figure 2f). This poor performance is due to an excess of exfiltration from the single aggregated SuDS

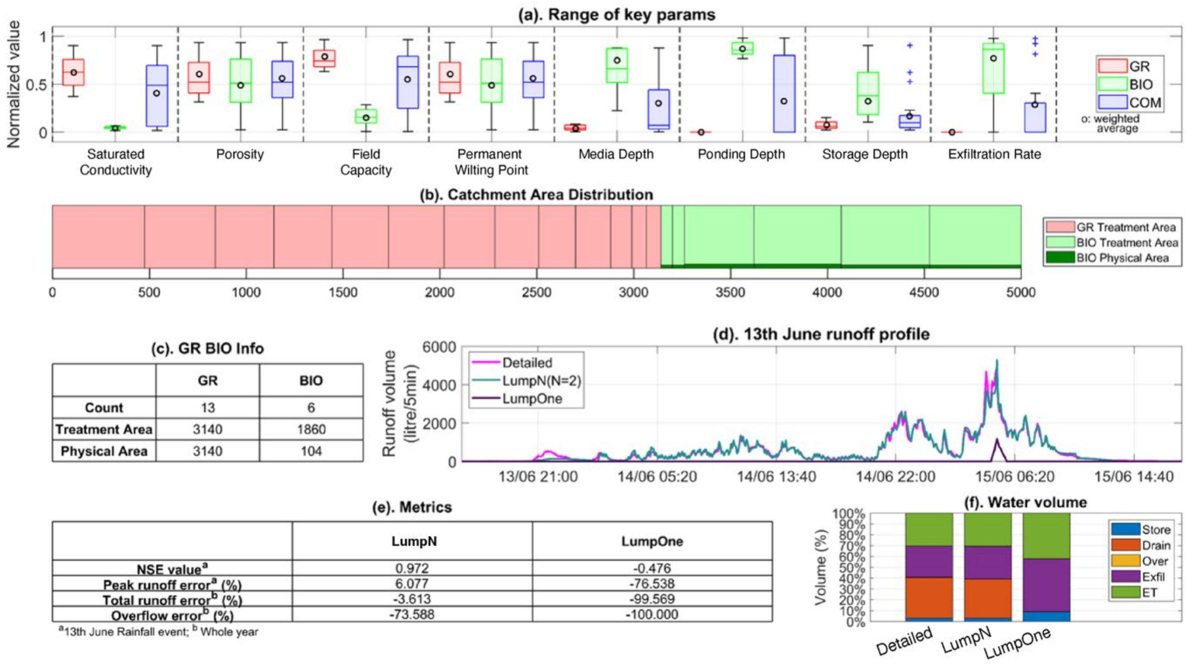

Figure 2. Aggregation strategy performance summary for an individual case. (a) Range of key parameters; (b) Catchment area distribution schematic diagram; (c) GR and BIO area information table; (d) Outflow profiles for 13th June event; (e) Performance metrics table; (f) Annual water balance.

in comparison to either the fully disaggregated baseline or the *LumpN* method. Other cases from the 500 simulated examples demonstrate better *LumpOne* prediction when there is less diversity in SuDS type (i.e. dominated by GR or BIO) and more homogeneity in SuDS configuration.

Figure 3 presents the distribution of performance metrics for the two SuDS aggregation methods across the 500 Monte Carlo simulations compared with the disaggregated baseline scenarios. The NSE results demonstrated that the *LumpN* strategy significantly outperformed *LumpOne*, with consistently higher NSE value and narrower interquartile range (Figure 2a). *LumpOne* also displayed poor peak outflow prediction performance in the June 13th rainfall event, with large error magnitudes and underestimation of peak outflow in all simulations (Figure 3b). Whilst *LumpN* had better peak outflow prediction performance, the presented boxplot exhibits non-negligible spread reflecting uncertainty of the prediction under certain SuDS configurations. Both *LumpN* and *LumpOne* underestimated the outflow volume (Figure 3c). These underestimations were due to an over estimation of exfiltration in aggregated systems, which reduced the simulated outflow to the sewer network.

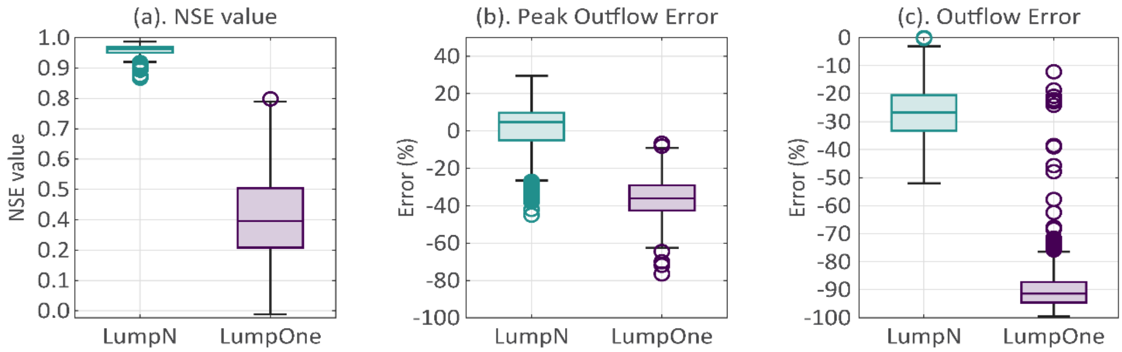

Figure 2. Aggregation strategy performance metrics: (a) NSE of annual outflow profile. (b) Peak outflow error for June 13th event. (c) Annual outflow volume error.

4 CONCLUSIONS

This study evaluated the hydrological prediction accuracy of different SuDS aggregation methods at the street scale. Two aggregation strategies (*LumpN* and *LumpOne*) were compared with a disaggregated baseline scenario. The results demonstrate that the *LumpN* aggregation strategies, which aggregate SuDS by type, can achieve comparable accuracy to fully detailed models. This indicates that type-specific aggregation, even when simplifying device-level variability, preserves the essential hydrological characteristics of the devices. In contrast, the *LumpOne* strategy, which combines all SuDS into a single composite unit, led to significant errors in outflow and overflow predictions. These errors were particularly pronounced in scenarios with a large number of BIO units or imbalanced GR:BIO distributions. In summary, *LumpN* aggregation provides a robust and computationally efficient approach to SuDS modelling at the street scale. In contrast, full aggregation (*LumpOne*) should be applied with caution, particularly when the system includes structurally and hydraulically diverse SuDS types. These findings provide practical guidance for urban planners and hydrological modellers seeking to balance accuracy and efficiency in large-scale SuDS performance assessments.

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