Scalable model simplification for hydrodynamic sewer system models

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Highlights

- A scalable procedure for automatic simplification of hydrodynamic sewer models is presented
- It also covers looped and very large networks, is fast and, thus, is applicable to practice
- Topological maps assist in the understanding of the system.
- Simplified models are useful for long-term evaluations in large search spaces (e.g. SUDS planning)

Introduction

Numerous tasks in urban drainage require the evaluation of many different potential options and scenarios over longer time periods (for example, planning or selection of design or operational measures to improve the drainage system, for example, Abasi *et al.* (2024)). Often, a detailed hydrodynamic model of the case study is available as an accurate description of the system. Despite current engineering practice (simplifying models to some extent), encouraging results of use of simplified models (e.g. Jakobsen *et al.* 1993, Farina *et al.*, 2023) and recent research on topological analysis of network structures (e.g. Bartos and Kerkez, 2019, Hesarkazzazi *et al.*, 2022, Reyes-Silva *et al.*, 2020, Simone *et al.*, 2023), yet a method is missing, which allows simplification of urban drainage networks including typical features such as loops, also for very large networks within limited time. Due to the possibilities of combining hydrological and hydrodynamic modelling approaches within one simulation model (Schütze and Alex, 2022), the procedure presented in this contribution allows a scalable procedure of model simplification, thus permitting the user to choose the degree of simplification required whilst ensuring that important hydrodynamic aspects are still covered also within the simplified model.

Methodology

The model simplification procedure starts with a hydrodynamic (detailed) model of the urban drainage network under consideration (denoted here as "Start model"), implemented in the Simba# simulator (ifak, 2022). Besides additional features, Simba# includes, as any other hydrodynamic simulator, full rainfall runoff modelling and solves the full Saint Venant equations when simulating urban drainage networks. Interface routines also allow to import networks implemented in other simulators, such as SWMM (Rossman, 2015) or Hystem-Extran (itwh, 2022). The scalable model simplification procedure consists of the four steps summarised in Figure 1.

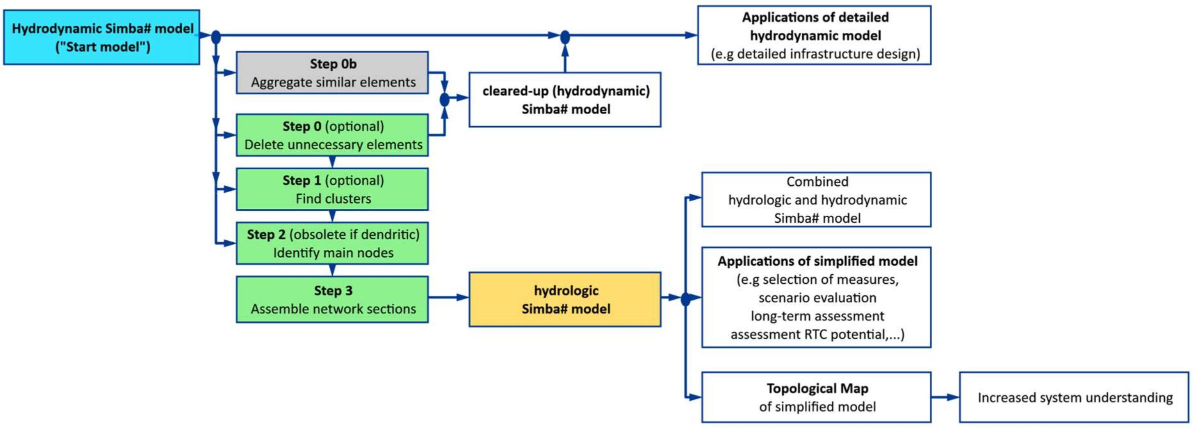
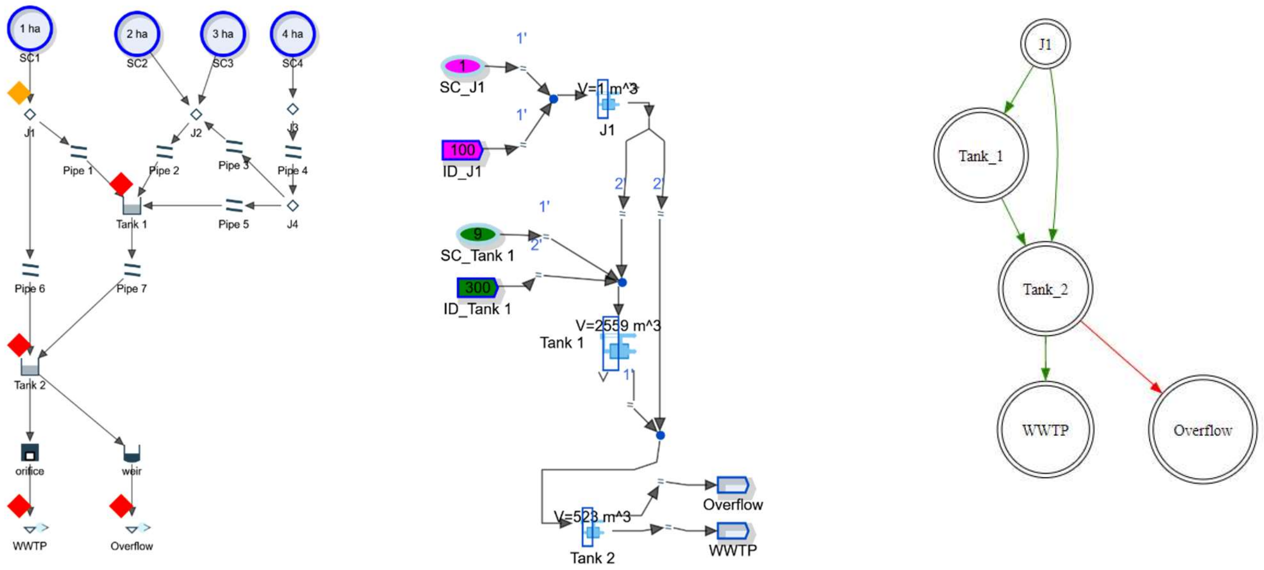


Figure 1. Overview of the scalable model simplification procedure

Step 0 consists in a preparatory analysis of the network, identifying non-connected individual nodes or stretches of pipes without any inflows. Such network elements occasionally are included in sewer models when their structure has been imported from GIS information. An extension of Step 0 (denoted here “Step 0b”) would consist in merging pipes and subcatchments of similar characteristics, as this has been proposed by many researchers (e.g. Schindler *et al.* 2007, Kroll, 2019) and which , in fact, is current practice when applying hydrodynamic models. Such aggregation of similar pipes might also be necessary for maintaining the Courant condition. However, such reduction usually still does not yield the simulation performance required for analysis of large search spaces and/or numerous long-term simulation runs. As these reductions of Step 0b are covered by current modelling practice, this Step 0b is not further discussed here.

The optional Step 1 aims at the identification of topologically independent networks contained in the Start model. Whilst in some cases (i.e., separate, isolated villages), it is obvious that their network is completely independent from the other sections, in some cases identification of independent networks might not be that obvious (such as separated rainwater networks within a city). Step 1 identifies the complete set of topologically independent networks (denoted here as “clusters”), by performing a topological backtracking analysis starting from all outfalls of the system. Subsequent steps, then, can focus on those clusters which contain the main parts of the system. As the application section will illustrate, in many cases, however, the modelled network will consist only in one cluster, covering the entire network.

Step 2 (which would be obsolete for purely dendritic networks) allows the user to specify network elements of particular interest, which are to be included under any circumstances also in the simplified model. A default selection would be the system’s main outfalls, its storage structures, but also special structures such as inverted syphons or important pumping stations. By specifying these elements, the user can influence the degree of simplification being carried out (extreme cases being: marking all elements would result in the simplified model identical to the start model, whilst marking only the outlets to the WWTPs could result in a simplified system merely consisting in just one catchment plus tank, aggregating the entire system in these elements). Figure 2 shows in red colour those network elements selected in the illustration example as initial elements for Step 2. Carrying out a topological analysis of the network, Step 2 identifies those network elements which are necessary to be added in order to get a (topologically) complete description of the simplified network (marked in orange). This procedure also ensures that that the amounts of areas and dry-weather flows are assigned to the corresponding network sections, thus maintaining their total sums.



(a) (b) (c)

Figure 2. Demonstrational model: (a) detailed hydrodynamic model, (b) simplified model, (c) Topological Map

Based on those elements identified in the previous step, the main part of the procedure – Step 3 – builds the simplified model, constructing a simplified model for each network section (see Figure 3) with each network section corresponding to an element identified in Step 2. This step also includes the automated calculation of the nonlinear volume-level storage curves within each network section, considering the pipe geometry and slope data of all pipes of the detailed hydrodynamic model assigned to that network section. Each network section aggregates the areas (maintaining the different categories of pervious and impervious areas according to the new German A102 guideline, and their rainfall runoff processes, whilst pipe storage and hydraulics are also aggregated in a combination of tank, storage pipe (if applicable) and transport pipes. Furthermore, besides the ready-to-run simplified model, a topological map (graphical representation of the network structure of the simplified model) is created, which provides the user with a quick-and-easy-to-grasp understanding of the network structure also of the original network. Figure 2 shows (b) the simplified model and (c) the corresponding topological map for the example network. Whenever the procedure detects an important bifurcation point within a system, it is included in the simplified model and a message is given, inviting the user to analyse that point in detail or to include a section of the hydrodynamic model at this location.

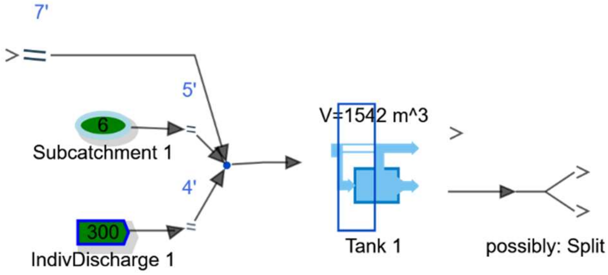


Figure 3. A network section

Whilst the resulting simplified model is ready to run (with a freely definable time step), it also can be subjected to a calibration and validation exercise. However, network sections known to be subject to important hydrodynamic effects (such as backwater effects in large interceptor sewers and its contributory pipes) can be substituted by the respective parts of the detailed hydrodynamic model, as Simba# allows to combine hydrologic and hydrodynamic modelling modules within the same model (Schütze and Alex, 2022). Hence, a simplified model is obtained which is characterised by high performance, yet maintaining important hydrodynamics.

Case studies

The procedure outlined above has been implemented and applied on several real-world sewer systems from different countries (Canada, Colombia, Germany) of different sizes (see Table 1). The systems represent combinations of combined and separate sewer network and have been taken from practical application projects and, thus, are not merely academic examples. Table 1, in its first part, summarises some key characteristics of the hydrodynamic network models used in these projects. Simulation times required obviously depend on a number of settings, but for each of the networks discussed here, typical simulation settings have been chosen. In each of these projects, a large number of potential measures is to be analysed, thus using the detailed models directly (without simplification) would not be feasible (except for Network No. 1, the smallest example).

Results and discussion

The lower section of Table 1 indicates some key numbers related to the steps of the simplification procedure. It can be seen that the procedure achieves model simplification with a significant reduction of simulation time. Even considering that the simulation times of the simplified model as given in Table 1 refer to a hydrological model – and substituting some network sections by their hydrodynamic counterparts certainly increasing simulation times to some extent - , even the combined hydrological-hydrodynamic simulation model does have simulation times permitting to carry out simulation runs for a large number of scenarios/options and/or under long-term evaluation scenarios.
Obviously, the validity of the simplified model needs to be confirmed in detail (and, if necessary, a calibration – validation exercise to be carried out), but with short simulation times, after having achieved the main step of topological model simplification as presented in this paper, this appears to be feasible.

Table 1. Network characteristics of the four application cases and performance of the simplification procedure

	Network 1	Network 2	Network 3	Network 4
# Subcatchments:	47	1658	11245	33446
# Pipes:	56	738	23188	41139
# Nodes (junctions + storage junctions)	57	721	23286	38615
Simulation time* for 1 day (detailed model)	6,3 sec.	16 min.	3 hours	9 hours
Step 0: #Nodes suggested for deletion	4	71	3997	6321
Step 1: #Clusters before	1	3	188	9
Step 1: #Clusters after	1	1	1	1
Step 2: #user-selected elements	9	4	40	100
Step2/3: # resulting network sections	9	8	58	241
Step 3: # bifucations identified	0	4	16	142
Simulation time* for 1 day (simplified model)	0,09 sec.	0,5 sec.	0,4 sec.	3,5 sec.
Processing time for simplification procedure:	sec.	sec.	min.	min.
Step 0: Delete unnecessary elements	<0,1	0,3	3,6	15,8
Step 1: Identify clusters	<0,1	0,5	14,8	71,3
Step 2: Identify main nodes	<0,1	0,2	48,7	45,9
Step 3: Assemble network sections	1,6	2,7	11	178,9
SUM:	1,9	3,7	78,1	311,9

* As simulation time steps 5" or 10" were used in the detailed model and 1' in the simplified mode

Conclusions and future work

A method for simplification of detailed hydrodynamic models has been developed and applied for various networks of different sizes, including also highly-looped and large networks. Even the largest of the networks analysed could be simplified in less than 6 hours. The degree of simplification can be streamlined; furthermore, combining hydrodynamic with hydrological modelling approaches in the simplified model allows to consider also hydrodynamic effects in the simplified model. Such simplified models are explainable and can also be modified easily, thus provide certain benefits in comparison to black-box type of models. Topological maps, resulting as a “by-product” facilitate understanding the structure of the network under study. Such simplified models will be useful also when linked with wastewater treatment and river models and/or when using them with Artificial Intelligence modules (e. g. Ogurek *et al.*, in print).

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References

Abasi, H., Schütze, M., Duchesne, S., Pelletier, G. (submitted): Combining Different Measures for Mitigating Combined Sewer Overflows in the Québec-Beauport system; 16th Int. Conf. on Urban Drainage, Delft, June 2024

Bartos, M., Kerkez, B. (2019): Hydrograph peak-shaving using a graph-theoretic algorithm for placement of hydraulic control structures, Advances in Water Resources, 127, 167-179

Farina, A. Di Nardo, A., Gargano, R., van der Werf, J.A., Greco, R. (2023): A simplified approach for the hydrological simulation of urban drainage systems with SWMM, Journal of Hydrology, 623, 129757

Hesarkazzazi, S., Bakhshipour, A.E., Hajibabaei, M., Dittmer, U., Haghighi, A., Sitzenfrei, R. (2022): Battle of centralized and decentralized urban stormwater networks: From redundancy perspective, Water Research, 222, 118910

ifak (2022): Simba#, Version 5, Manual, ifak e. V., Magdeburg, Germany

itwh (2022): Hystem-Extran, Version 8.5, Documentation, itwh GmbH, Hannover, Germany

Jakobsen, C., Hansen, D.B., Harremoes, P. (1993): Development and application of a general simulator for rule based control of combined sewer systems. 6th International Conference on Urban Storm Drainage. Niagara Falls, 1357-1362

Kroll, S. (2019): Design of Real-Time Control Strategies for Combined Sewer Networks; PhD thesis; Katholieke Universiteit Leuven

Meijer, D., Korving, H., Clemens-Meyer, F., 2022. A topological characterisation of looped drainage networks. Structure and Infrastructure Engineering. DOI: 10.1080/15732479.2022.2152464

Ogurek, M., Schütze, M., Alex, A. (in print): Integration of selected AI methods into a simulation tool for urban wastewater systems - towards practical examples; at-Automatisierungstechnik; in print

Reyes-Silva, J.D., Zischg, J., Klinkhamer, C., Rao, P.S.C., Sitzenfrei, R., Krebs, P. (2020): Centrality and shortest path length measures for the functional analysis of urban drainage networks, Applied Network Science, 5, 1

Rossman, L. A. (2015): Storm Water Management Model User’s Manual Version 5.1., US Environmental Protection Agency

Schindler, N., Krebs, P., Ogurek, M., Schütze, M. (2007): Vereinfachte integrierte Modelle der Abwasserentsorgung zur Analyse von Steuerungsstrategien. KA-Abwasser, Abfall, 54, 6, 577 – 583

Schütze, M., Alex, J. (2022): A Multi-Domain Solver for integrated modelling; 12th Urban Drainage Modelling (UDM) conference; Costa Mesa, USA, 10. – 12.01.2022

Simone, A., di Cristo, C. Guadagno, V., del Giudice, G. (2023): Sewer networks monitoring through a topological backtracking, Journal of Environmental Management, 346, 119015