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# Development of a fast urban flood model for real-time applications

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**Abstract**

Detailed 1D/2D models have become standard practice for urban flood modelling. However, many applications require computationally fast simulation models. Due to their prolonged calculation times, these 1D/2D models are unsuited for such applications. This research compares three modelling approaches with different levels of complexity and simulation times: (1) a highly detailed 1D/2D model, (2) a 1D/1D model with two different flood cone parameterizations, and (3) a newly developed surrogate dual drainage model. The three approaches are tested and compared on a Belgian case study. Results show that the surrogate dual drainage model can emulate the results of highly detailed models with calculation time reductions in the order of magnitude of $10^{5.}$

## 1 Introduction

The last decades, the increase in computational power has resulted in a shift in urban drainage modelling approaches. Detailed 1D/2D models have become standard practice for many operational managers. This shift is also evidenced by the different software packages that emerged in the past decade, like SOBEK (Deltares, 2017), XP-SWMM 2D (XP Solutions, 2014) and InfoWorks ICM (Innovyze, 2015) among others. This 1D/2D approach models the subsurface using 1D connections, while the surface is included as a two-dimensional mesh based on a high resolution digital terrain model (DTM). Hence, such 1D/2D models are far more detailed than conventional 1D/1D models, which use flood cones as a simplified representation of the true topography. This additional level of detail results in more accurate predictions, but also far greater computational times. This impedes their use for real-time applications, or investigations that require a great number of model runs, such as strategy development, optimization problems and uncertainty analyses. Improvements in computational power in the next decades will likely not solve this challenge.

Therefore, a need exists for surrogate models that can emulate the accuracy of the 1D/2D models, but with minimal computational efforts. This research developed such dual drainage-type surrogate model, suitable for many analyses and potentially real-time forecasting and control applications. It emulates the dynamics of the subsurface pipe network, while also accounting for the DTM to simulate urban floods. Hereto, a data-driven mechanistic approach is followed, in which the surrogate model is calibrated to results of a detailed 1D/2D model, and yet physically meaningful parameters are obtained.

This approach is tested by modelling a city in Belgium. A detailed 1D/2D model was set up, and four areas were selected where floods occurred in the past years. Next, a 1D/1D flood cone model was configured and compared to the results of the more detailed 1D/2D model. Finally, a surrogate model was created from the 1D/2D model, and compared to the other two models.

# 2 Methodology

## 2.1 Case study area and 1D/2D model

The districts of Sint-Amandsberg and Oostakker of the city of Ghent (Belgium) were selected as case study, as reports of recent flood events were available to validate the simulation models. The study area covers approximately 30 km² and is highly urbanized with a population equivalent of 43,626. A detailed 1D/2D InfoWorks ICM model was configured for the entire study area (Figure 1, left). The model is comprised of 6025 conduits, 5855 manholes and 182 hydraulic structures. A high resolution triangular mesh was set up to emulate the terrain with mesh areas between 3.75 m² to 50 m². Four locations of interest were selected to compare the different models based on reports of recent floods (marked in yellow, see Figure 1, left).

A set of 122 storm events were investigated in this study, consisting of 2 historical storms which resulted in significant flooding (28th of July 2013, 30th of May 2016) and 120 synthetic events created by a stochastic rainfall generator (Muñoz et al., 2015). The historical storms enabled validation of the model, while the synthetic storms were used to set up the data-driven surrogate model.

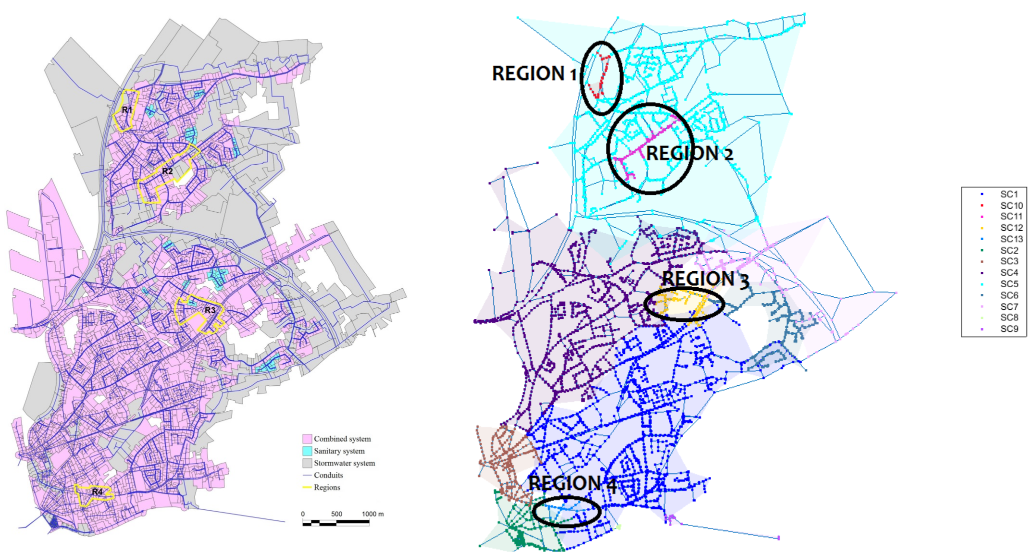


**Figure 1:** Left: 1D/2D model of the study area. The four locations of interest are marked in yellow. Right: Surrogate model with its division of the subsurface network in 13 interconnected storage cells.

## 2.2 1D/1D models: default and optimized parameters

Next, two 1D/1D models were configured using InfoWorks ICM. The first model (denoted as "Default flood cone model") comprised the default flood cone parameters of the InfoWorks software package, which are used most in practice. Hence, these parameters do not match the urban topography, and consequently do not require any data of the DTM. The flood cones in the second model ("Optimized flood cone model") were adjusted to match a high resolution DTM. The InfoWorks software constrains the possible parameter sets of flood cones, although a good fit to the DTM was possible.

## 2.3 Surrogate model

Finally, a surrogate modelling approach was developed based on the dual drainage approach. This model was calibrated (40 events) and validated (82 events) to simulation results of the detailed 1D/2D InfoWorks ICM model. The 122 events that were used for calibration and validation are based on rainfall data of the Royal Meteorological Institute of Belgium at Uccle. This station registered a unique 100-year series of 10-minute rainfall intensities. From this storm, different historical and synthetic storms (by combining parts of different historical events) with large rainfall intensities (peak 10-minute rainfall intensities above 15 mm/h) and/or cumulative volumes (independent volumes with the highest 6-hour cumulative rainfall). Out of the 122 storms, 15 were created by merging two storms, leading to events with two consecutive peaks. Such succession of peaks can have a major impact on urban flooding, as storages (in both the sewer and on the surface) can already be filled due to the first peak.

The subsurface was modelled according to the methodology developed by Wolfs & Willems (2017). First, the subsurface network of pipes and hydraulic infrastructure was aggregated into 13 interconnected storages (Figure 1, right). Experiments showed that creating fewer storages, and thus lumping sewer processes further, would lead to accuracy losses (tested in a trial-and-error procedure). Next, the flows between the different storages were modelled using various data-driven techniques, including simple regression models and more advanced neural networks. The reader is referred to Wolfs & Willems (2017) for more information on this approach.

The underground model is then connected to a surface model which simulates urban flooding. Given rainfall intensities and simulated storage volumes of the underground network, the surface model predicts surface flood volumes in the selected regions. Hereto, flood volumes are aggregated from the pre-defined areas of interest in the InfoWorks ICM model, and used as calibration and validation data. Hereto, a 100-year return period composite storm was simulated in the detailed InfoWorks 1D/2D model. The simulated flood extent in the four selected regions of this event were used to demarcate the pre-defined areas over which the flood volumes were lumped. Naturally, it is possible that the identified areas are still too small to capture the flood extent of certain storms, as the direction of passing storms and varying rainfall intensities could result in other flood extents in reality. However, out of the 122 simulated storms, none exceeded the identified flood extent. The surface model itself consists of a serial connection of two artificial neural systems: a classification network that can identify when flooding emerges, and an ensemble of five neural networks to quantify the magnitude of the flood. This serial connection of two (ensembles of) neural networks results in improved model predictions, as the first network can focus entirely on whether flooding occurs or not, and the second ensemble is aimed at mimicking the magnitude of the flood. In addition, by using an ensemble of neural networks, the generalization capabilities are improved and the risk of overfitting is reduced. Experiments showed that a one-layer classification neural network with 10 hidden nodes yielded satisfying results, while one-layer neural networks with 15 to 25 hidden nodes were used for mimicking the magnitude of the flood. The flood volumes can be transformed via various existing GIS spreading algorithms to produce flood maps.

# 3 Results and discussion

The simulation times of the three simulated models differ significantly. The 1D/2D model takes approximately 408 CPU minutes to simulate a 6-hour event and the 1D/1D models 91 CPU minutes on an i7 processor at 3.40 GHz and 16 GB RAM. The surrogate model, however, requires less than a second to simulate the same event using a single core. This vast speed gains enables numerous (real-time) applications that require a large number of simulations.

Figure 2 shows the simulated flood volumes at the four locations of interest ('R1' to 'R4') of the four models for the historical May 2016 event.

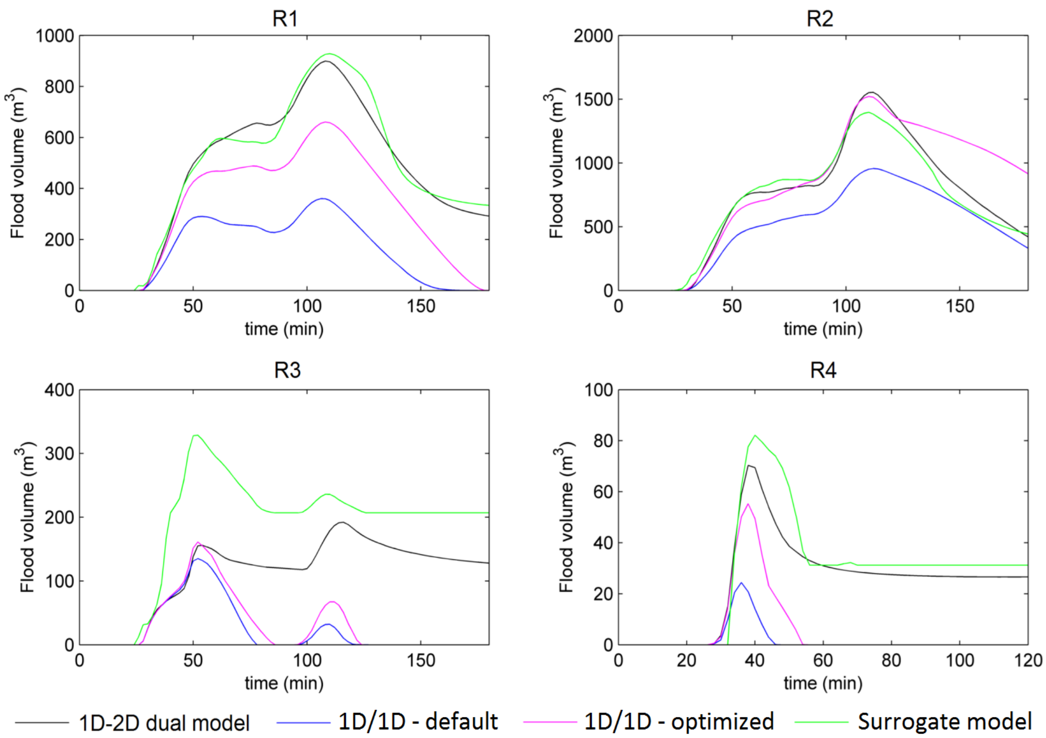


**Figure 2:** Simulated flood volumes of the 1D/2D model, the 1D/1D flood cone models (with default and optimized parameters) and the newly developed surrogate dual drainage model.

Flood reports of the storm of May 2016 evidenced that flooding occurred at these four locations. Unfortunately, no precise flood volumes nor durations were available to perform a more detailed model validation. Hence, the 1D/2D InfoWorks ICM model is assumed to match reality closest based on the incorporated level of detail. The other models are thus compared to the results of this detailed 1D/2D model.

The figure shows that the 1D/1D model with default flood cone parameterization underestimates the flood volumes significantly at all locations. The 1D/1D model with optimized flood cone parameters using information of the DTM yields maximum flood volumes that match those of the 1D/2D model closer. This evidences the importance of accurate flood cone parameterisations. However, the maximum flood volumes are still underestimated by the 1D/1D model. Secondly, the simulated flood volumes in both 1D/1D models decrease too rapidly after the peak of a storm. This is expected, as the volume in a flood cone remains directly connected to the underground system. Hence, if capacity becomes available in the subsurface network, the volume on the surface is drained immediately. In reality, part of the volume remains present in local depressions.

The surrogate model emulates the results of the 1D/2D model much closer in regions R1, R2 and R4. In region R3, the surrogate model succeeds in predicting the moment of inundation correctly, but overestimates the maximum flood volume significantly. Performance can be increased by using more advanced neural networks (e.g. a higher number of neurons) and including more training data. Note that increasing the number of neurons (and thus increasing the model emulation capabilities), also increases the risk of overfitting. Therefore, a balance must be found between increasing the model complexity, and adding sufficient training data to ensure the generalization capabilities. The flood duration is emulated more accurately by the surrogate model than both 1D/1D models. It is clear that the receding flood volume is simulated more realistic than using flood cones.

Table 1 summarizes the performance metrics for the locations of interest for both historical storms. These confirm the results above. The results for the July 2013 storm are comparable to those of the May 2016 event.

| | | **1D/1D - default** | | | | **1D/1D - optimized** | | | | **Surrogate** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Event** | **Metrics** | **R1** | **R2** | **R3** | **R4** | **R1** | **R2** | **R3** | **R4** | **R1** | **R2** | **R3** | **R4** |
| May 2016 | NSE | -0.52 | 0.67 | -2.47 | -1.33 | 0.66 | 0.80 | -2.06 | -0.63 | 0.98 | 0.97 | -1.17 | 0.80 |
| | Δvol (m3) | -539 | -597 | -57 | -46 | -239 | -32 | -31 | -15 | 29 | -157 | 136 | 12 |
| | Δvol (%) | -60 | -38 | -30 | -65 | -27 | -2 | -16 | -21 | 3 | -10 | 71 | 17 |
| July 2013 | NSE | -0.16 | 0.54 | -0.57 | -0.25 | 0.61 | 0.97 | -0.37 | 0.42 | 0.96 | 0.94 | 0.61 | 0.94 |
| | Δvol (m3) | -198 | -234 | -45 | -80 | -80 | -82 | -23 | -26 | -39 | -87 | 39 | -1 |
| | Δvol (%) | -52 | -40 | -43 | -67 | -21 | -14 | -23 | -22 | -10 | -15 | 37 | -1 |

**Table 1.** Performance indicators for the investigated locations ('R1' to 'R4') for the 1D/1D models (default and optimized flood cone parameters) and the surrogate model for two historical storms (validation data). NSE: Nash Sutcliff Efficiency; Δvol: difference in maximum flood volume compared to the 1D/2D model.

As surrogate model 2 is mostly data-driven, it also comes with certain limitations. Only dynamics that are included in the calibration (training) data set can be mimicked, as it is uncertain how the model will act outside its calibration range. Therefore, it is vital to include as diverse and as much training data as possible, and to test it under various (extreme) conditions. This was achieved in this study by using 122 different calibration and validation events. When sufficient and reliable data is unavailable, the level of detail of the surrogate model has to be reduced, and thus the model performance will likely decrease too. Secondly, setting up surrogate model 2 requires calibration. However, the calibration process of the surrogate model can easily be automated completely if sufficient data is available (or simulation results of more detailed hydrodynamic models are being used as an approximation of reality), and is thus not time consuming.

# 4 Conclusions

Three modelling approaches were compared to simulate urban flooding on a case study in Belgium: a highly detailed 1D/2D model with a high-resolution DTM, two 1D/1D models with different flood cone parameterisations, and a newly developed surrogate model. The results show that the parameterisation of the flood cones has a significant impact on the simulated flood volumes. Secondly, flood cones are not well suited to simulate flood durations accurately. The surrogate model managed to simulate both flood volumes and durations far more precisely. In addition, the simulation time of the surrogate model amounts less than 1 CPU second, compared to respectively 408 and 91 CPU minutes for the 1D/2D and 1D/1D models. Hence, the developed surrogate modelling approach has great potential for applications that require models with minimal simulation times, such as real-time applications and optimization problems.

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