Simplification of one-dimensional hydraulic networks by automated processes evaluated on 1D/2D deterministic flood models

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ABSTRACT

Evaluation of pluvial flood risk is often based on computations using 1D/2D urban flood models. However, guidelines on choice of model complexity are missing, especially for one-dimensional (1D) network models. This study presents a new automatic approach for simplification of 1D hydraulic networks (SAHM) using trimming and merging techniques, with performance evaluated in a 1D/2D case study. Decreasing the number of elements in the 1D model by 66% yielded a 35% decrease in computation time of the coupled 1D/2D simulation. The simplifications increased flow in some downstream branches and removing nodes eliminated connection to some areas. This promoted errors in two-dimensional (2D) flood results with changes in spatial location of flooding in the reduced 1D/2D models. Applying delayed rain inputs to compensate for changes in travel time and preserving network volume by expanding node diameters did not improve overall results. Investigations on the expected annual damages (EAD) showed that differences in EAD are smaller than deviations in the simulated flooded areas, suggesting that spatial changes are limited to local displacements. Probably, minor improvements of the simplification procedure will further improve results of the reduced models.

Key words | 1D/2D urban flood model, computation time, flood damage cost, hydraulic network, model reduction

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ABBREVIATIONS AND NOTATION

1D	One-dimension(al)
2D	Two-dimension(al)
CSI	Critical Success Index
DEM	Digital elevation model
EAD	Expected annual damage
GIS	Geographic information system
NC	No compensations – used when no compensations for volume and travel time have been included in the simplified model
SAHM	Simplification algorithm for 1D hydraulic network models
T###Mxxx	Notation of models only trimmed by ### mm
TxxxM###	Notation of models only merged by ### metres
T###M###	Notation of simplified models both trimmed by ### mm and merged by ### metres

INTRODUCTION

Hydraulic models of urban drainage networks have been used for decades to evaluate the resilience of an area or test the effects of new infrastructure. With the main purpose of evaluating drainage capacities, for long it has been sufficient to simulate flows in the drainage network only. Naturally,

these physically based deterministic models are now also commonly used to support decision-making for climate adaption structures and urban development plans (Field *et al.* 2012). However, climatic changes and urban development are causing an increase in size and frequency of urban flooding leading to a need for local measures to reduce the impacts (Field *et al.* 2012; IPCC 2014). This means that overland flows must be included in the hydraulic models (Henonin *et al.* 2013). Compared to one-dimensional (1D) surface models, a more realistic description of surface flow patterns is obtained by using coupled 1D/2D models (Leandro *et al.* 2009).

The coupling of a 1D network model and two-dimensional (2D) surface model (1D/2D) has significantly expanded the application areas of urban flood models and these models are now commonly used to predict the extents of urban flooding (Henonin *et al.* 2013; Russo *et al.* 2015). The shift from 1D/1D to 1D/2D models dramatically increases the computational demand (Leitão *et al.* 2010; Henonin *et al.* 2013; Van Dijk *et al.* 2014). The computational demand is of high importance for applications in flood warning systems or simulation of multiple scenarios (Leitão *et al.* 2010; Henonin *et al.* 2013; Meneses *et al.* 2015). Therefore, numerous attempts at speeding up 2D simulations are described in the literature including multi-layered coarse grid simulations (Chen *et al.* 2012), reduced complexity models (McMillan & Brasington 2007), and using a cellular automata approach (Ghimire *et al.* 2013).

The extensive work and knowledge gathered on computation of 2D models has shown promising results with reductions from days and hours down to minutes. With no change in the 1D network model, the computational demand of the 1D model thereby accounts for a larger share of the total computational demand of the 1D/2D model. Naturally, the next step is to reduce the computational demand of the 1D network models.

Numerous studies have been dedicated to improvement of 1D hydraulic network models using various approaches including conceptual models (Wolfs *et al.* 2013) or simply reducing the number of elements in the network (Leitão *et al.* 2010). However, few have looked into the effects on 2D surface model results when reducing the level of detail of the 1D network for a coupled 1D/2D model.

Simplification of hydraulic networks is often conducted manually or semi-automatically using a geographic information system. These procedures require numerous subjective decisions. Guidelines for network simplification are scarce and only a few unofficial documents on good practice exist, e.g., Wastewater Planning Users Group (2002). Errors due to wrongly or over-simplified models (models with structural deficits) have been widely neglected according to Del Giudice *et al.* (2015), who attempt to capture the combined errors of inputs and structural model errors in a stochastic term. However, structural model errors can be reduced by setting up procedures for how the model complexity can be lowered. Furthermore, an automated tool will enable a more consistent practice as well as reduce time and resources needed when implementing model simplification.

The purpose of this paper is to present an approach for automatic simplification of the 1D component in 1D/2D flood models. We apply two different methods for network simplification along with a combination making a third approach. The approaches include compensations for the simplifications. The performance of the simplified models is evaluated by comparing to a baseline consisting of the full 1D/2D model whereby further development of the approach is identified.

METHODS

Three common approaches to network simplification are identified in Leitão *et al.* (2010), denoted pruning, trimming, and merging of links and nodes, respectively. Pruning is the most conservative method of only removing small, short links along main branches. This method has a very limited impact on computational demand and is rather a method to improve numeric model stability. Pruning is also included in the more comprehensive trimming approach that consists of deleting whole branches of links below a threshold for, e.g., diameter. Finally, merging involves joining multiple links to a single one by deleting nodes. Merging will maintain the extent of the network while trimming leads to the removal of the pipe network in some areas. Additionally, the approaches can be combined by merging links in an already trimmed model.

Simplification of large network models

An automatic simplification tool is developed, applying the approaches in a fast and efficient manner. The simplification

algorithm for 1D hydraulic network models, SAHM (Löwe *et al.* 2017), is newly developed in the open source programming language Python and input to the tool is extracted from a MIKE Urban geodatabase. The structure of the main script is shown in Figure 1(a). Prior to removal, the link or node must fulfil an extensive set of conditions. Using SAHM, simplification is completed within a few minutes, with an output ready for simulation without further modifications.

Trimming

The trimming module in SAHM performs the exclusion of pipes and branches below a certain diameter threshold defined by the user. This approach requires information of the connected branches. To fulfil this, the trimming algorithm is recursive, thus a starting point is defined from where the algorithm moves through the network, as illustrated in Figure 1(b). For each node, SAHM will check upstream branches and whether all links within the branch are below the threshold diameter. If so, the branch is removed. Otherwise, the starting point moves one node upstream and the search is restarted from the new starting point. Figure 1(d) describes this procedure. In some cases, the branch contains a loop that may compromise the approach described to this point. To handle this, comparing nodes in the branch to previous start-nodes identifies a loop. A loop will only be removed when all links within the loop fulfil the conditions.

Merging

The merging module in SAHM joins two neighbouring links to one and removes the common node from the network. The condition for merging is a lower threshold on link length. Contrary to trimming, the merging approach only processes one link and its neighbouring links at a time, as illustrated in Figure 1(c). The approach for selection of links to merge is described in Figure 1(e). An extensive set of conditions needs to be fulfilled before two links are merged. Initially, the length of the link is compared to the minimum length threshold. If the link is within the threshold, checks with neighbouring links begin, otherwise the search continues to the next link. Links are unsuitable for merging if they are parallel, have different type of

structure, or have large diameter differences. The user defines the diameter difference threshold. In addition, a node cannot be removed if it is an intersection between three or more links. When a link can be merged with links to both sides, the shortest one is selected for merging. Since the link resulting from merging two very short links can be shorter than the threshold, the merging of the network is repeated several times with gradually increasing lengths until the specified threshold is reached. As indicated in Figure 1(c), the total length of the pipe system is preserved, and hence the pipe length in the 1D simulation no longer corresponds to the physical length between the nodes in the reduced network.

Compensations

Modifying the hydraulic network as described will change the characteristics of flow. We attempt to compensate for the changes by modifying the network volume and the travel times as described in the following.

Reassigning sub-catchments and travel time

When nodes are removed, the sub-catchments connected to the removed node are reassigned to the nearest downstream node. Thereby, runoff from these sub-catchments reaches downstream nodes earlier. We compensate for this effect by applying a time delay on the catchment runoff. The time delay t_L is approximated using the Manning equation to calculate the flow velocity, u, assuming full flowing conditions:

$$t_L = \frac{L}{u} = \frac{L}{M \cdot R_h^{2/3} \cdot S^{1/2}} \qquad (1)$$

where t_L is flow time for a given link with Manning number M [m$^{1/3}$/s], hydraulic radius R_h, slope S, and length L.

Links with no or very low slope in the overall flow direction are assigned too long time delays when using this approach, since the acceleration, pressure and momentum descriptions from the Saint-Venant equations are neglected in the Manning equation used for the velocity approximation. Therefore, a threshold for minimum velocity is introduced for u in Equation (1). The threshold of minimum velocity has been defined to 0.15 m/s based on Wallington
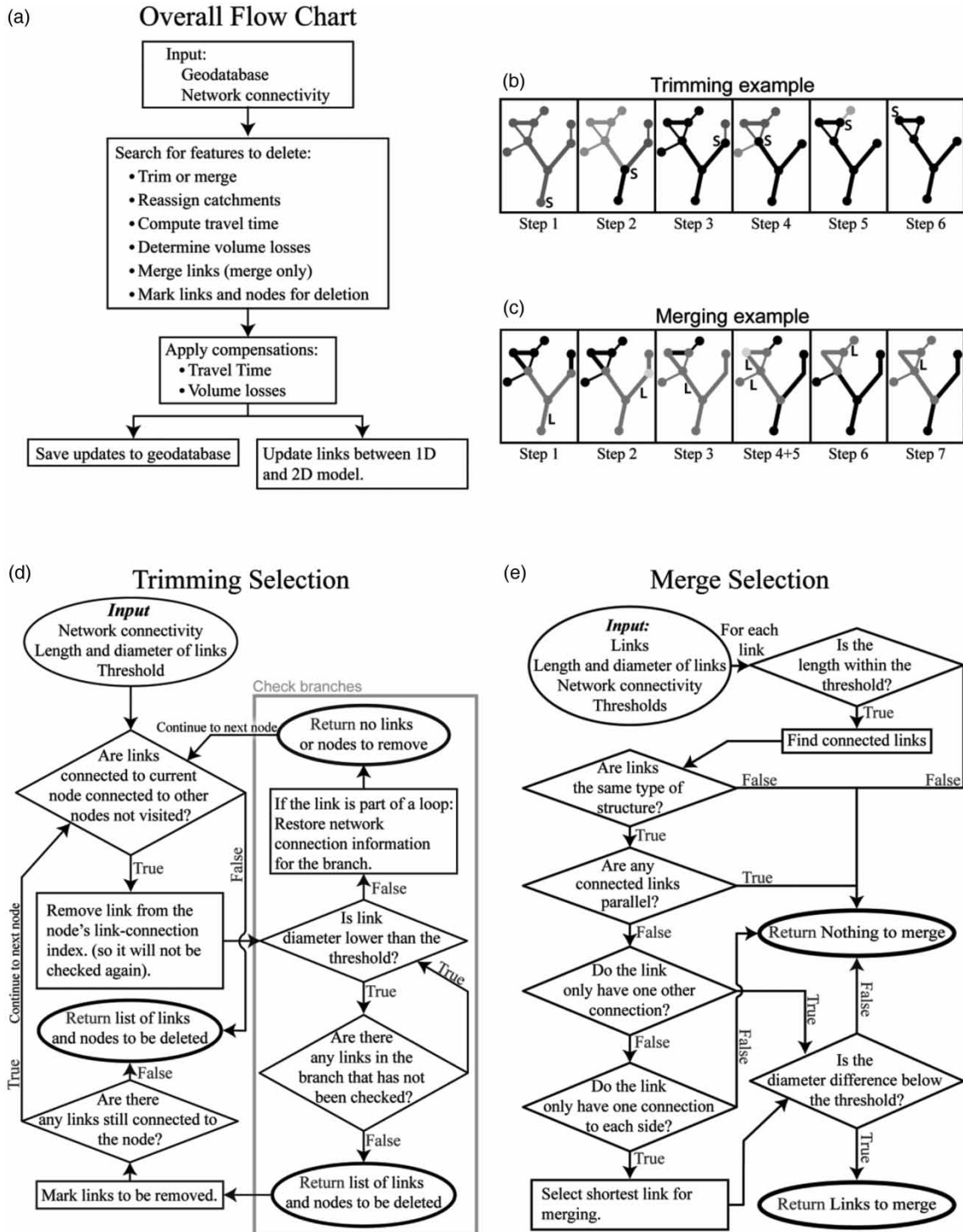
Figure 1 | (a) Main structure of SAHM including different modules. (b) Procedure of trimming selection approach, removing nodes and links. *S* indicates the starting node in the search for branches to remove. Branches are considered individually as indicated by different colour shades. Only when all links in the branch fulfil the conditions, the branch is removed. Equally, loops are only removed if all links fulfil the conditions. If none of the branches fulfil the conditions, the search moves to the next upstream node. If multiple nodes exist upstream, these are considered as separate starting points. (c) Procedure of merging approach, removing nodes. *L* indicates the link from where the conditions of merging are checked with neighbouring link(s) one by one. Light grey nodes fulfil the conditions for merging. (d) The approach for selecting links to delete when trimming using SAHM. (e) The approach for selecting links to merge in SAHM.

charts (Butler & Davis 2011). If the computed velocity for a link is below this threshold, the velocity of the upstream neighbouring link is applied if this exceeds the threshold. Otherwise, the threshold value is assumed as the velocity for the link in the estimation of time compensation.

The total time delay for each catchment, t_T, is computed as the sum of flow times for all links between the newly assigned network node and the original as:

$$t_T = \sum_{k=1}^{n} t_{L,k} \tag{2}$$

for the n links on the flow path, each with a flow time t_L. The total time delay is implemented by assigning a time delayed rainfall time-series to each sub-catchment.

Volume losses

When parts of the network are removed during simplification, the physical volume of the simplified network is smaller than that of the original network. With lower storage in the hydraulic network, water might be stored in the surface compartment causing flooding and provoke errors in simulated surface flooding. We compensate for volume losses by increasing the volume of nodes downstream from removed elements. Thereby, we maintain the maximum flow rate of the remaining links in the network. The total volume compensation V_c is calculated for each deleted pipe and node and summarised for the branch that is removed as:

$$V_c = \sum_{i=1}^{n} V_{L,i} + \sum_{j=1}^{m} V_{N,j} \tag{3}$$

where V_L and V_N are volume of the ith link and j^{th} node, respectively, which is summarised for the n links and m nodes on the flow path giving the total compensation volume, V_c.

The total volume compensation V_c is added to the volume of the existing node, V_{node}, where compensations are implemented, and a new diameter, D_{new}, of the node is calculated as follows. Maintaining the height of the node, h_{node}, prevents changes of the maximum pressure head.

$$D_{new} = 2 \cdot \sqrt{\frac{V_{node} + V_c}{h_{node} \cdot \pi}} \tag{4}$$

In the trimming procedure, the volume compensation applies to the node where the deleted branch was attached. In the merge procedure, the diameter is changed in the node immediately downstream of the merged links.

Assessing performance of the simplified models

The simplified models are compared to the baseline model by means of traditional metrics such as computation time, hydrographs and mass balances. We also introduce two metrics that assess the importance of the spatial distribution of the model errors in their typical use, i.e., calculation of hazard maps and overall risk of flooding in the catchment. The metrics are described below.

To quantify the spatial errors of the hazard maps, we use contingency tables for each simulation comparing hits (overlapping pixels), misses (only flooding in baseline) and false positives (only flooding in simplified model). To summarise the results across the many models we use the Critical Success Index (*CSI*) introduced by Bennett *et al.* (2013):

$$CSI = \frac{\text{hits}}{\text{hits} + \text{misses} + \text{false positives}} \tag{5}$$

Flood risk is often summarised as the expected annual damage (*EAD*) (Zhou *et al.* 2012). The *EAD* is computed from the damage costs and hence differences in *EAD* will indicate the ability of the simplified models to generate results that are correct on the catchment level in relation to decision-making.

The *EAD* is calculated as (Olsen *et al.* 2015):

$$EAD = \frac{1}{2} \sum_{i=1}^{n} \left(\frac{1}{T_i} - \frac{1}{T_{i+1}} \right) (D_i + D_{i+1}) \tag{6}$$

where T_i denotes the ith return period being considered and D_i the total damage corresponding to return period T_i. Throughout all analyses, return periods of 2, 5, 10, 20 and 100 years are used as recommended by Olsen *et al.* (2015). The total cost of flood damages are in this study calculated as a function of water depth for roads and buildings of both residential and commercial categories. For residential buildings, we further distinguish between structural and content damage in the building. The costs and depths used in the damage functions are specified in Table 1.

Table 1 | Thresholds for damage to different types of structures and costs

Type	Threshold for damage	Cost range
Building – Commercial	10 cm (210)	162–852 AUD/m^2
Building – Residential		
Content damage	10 cm (300)	7,200–53,400 AUD/ building
Structural damage	20 cm (300)	40,751–190,171 AUD/ building
Road	30 cm	3.71 AUD/m^2

Numbers in brackets specify the water depth where the maximum damage cost occurs. Damage cost are obtained from Olesen *et al.* (2016)

With the damage calculated for multiple return periods, we use Equation (6) to calculate the EAD, as illustrated in Figure 2.

CASE STUDY

A 1D/2D urban flood model is used for testing SAHM. The model is set up in MIKE FLOOD and covers the Elster Creek catchment located in the suburbs of Melbourne, Australia (Figure 3). The area has recently experienced several large floods (Victoria State Government and Melbourne Water 2016). The 1D network model contains 10,415 links, 10,011 nodes and 12,113 sub-catchments covering 48.7 km^2 including 19.6 km^2 impervious areas. The 2D surface is built from a mesh with 399,257 pixels of 10×10 m and has been limited to areas where flow on the surface may occur to reduce
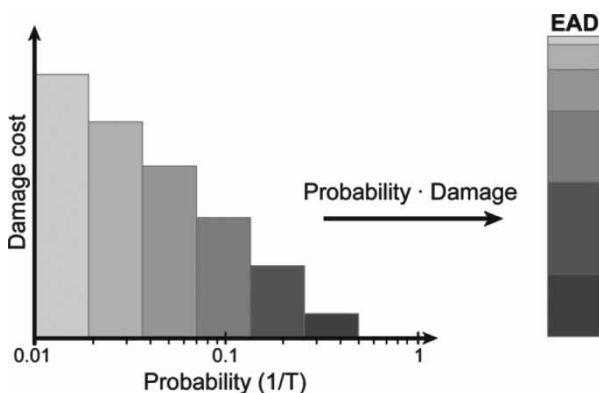

Figure 2 | Concept of EAD calculations. Equation (6) is used to calculate the area under the damage curve by interpolating between the damage costs determined for different return periods.

computation time. Therefore, the mesh covers only 40 km^2 of the catchment. Simulations are performed using a time-step of 2 seconds, both for the 1D network model and for the 2D surface model, in all considered scenarios.

The fully dynamic Saint-Venant equations are used for calculating flow in the 1D network via the six-point Abbott-scheme. Flow in the 2D model is simulated using the full shallow water equations with a higher order numerical scheme and a finite volume method. For additional information on the 2D solution scheme used in MIKE FLOOD, see DHI (2014, 2015). The two models are linked at each node using a virtual orifice for calculation of water exchange.

The hydraulic network primarily consists of circular links draining most catchments. A large open channel drains the area from mid-west to the northwest as the main outlet to the sea. Two additional outlets are located north and south of the main outlet. Both of these are closed rectangular channels with the southern one connected to the open channel, while the other drains the northern part of the network. The northwest part of the catchment is a low-lying area exposed to flooding from high sea levels. In this study, the sea level is kept constant at an elevation of 0 metres as we focus on flooding from the drainage system only. The upstream part of the catchment is steeper and flooding in this area is caused by precipitation only.

A baseline is produced from model simulations with different rain inputs. Design rain inputs with return periods of 2, 5, 10, 20 and 100 years were obtained from the Australian Bureau of Meteorology (BOM 2016) and are used for simulation. To obtain an indication of the uncertainty of the simulated flood extent resulting from other sources than simplification we have increased and decreased the rain volume by 23%, corresponding to the overall uncertainty of runoff according to Hansen & Liu (2004).

Table 2 gives an overview of the 1D models used for simulation in the baseline and after simplification. The simplified models are denoted as T###M### with T denoting a model where links smaller than this threshold diameter in mm were trimmed, while M denotes where links shorter than the threshold in metres were merged. The notation xxx marks that either the trimming or merging module is not used for the simplification. Further, some models are denoted with 'NC' as an abbreviation for 'no compensations', thus no time and volume compensations have
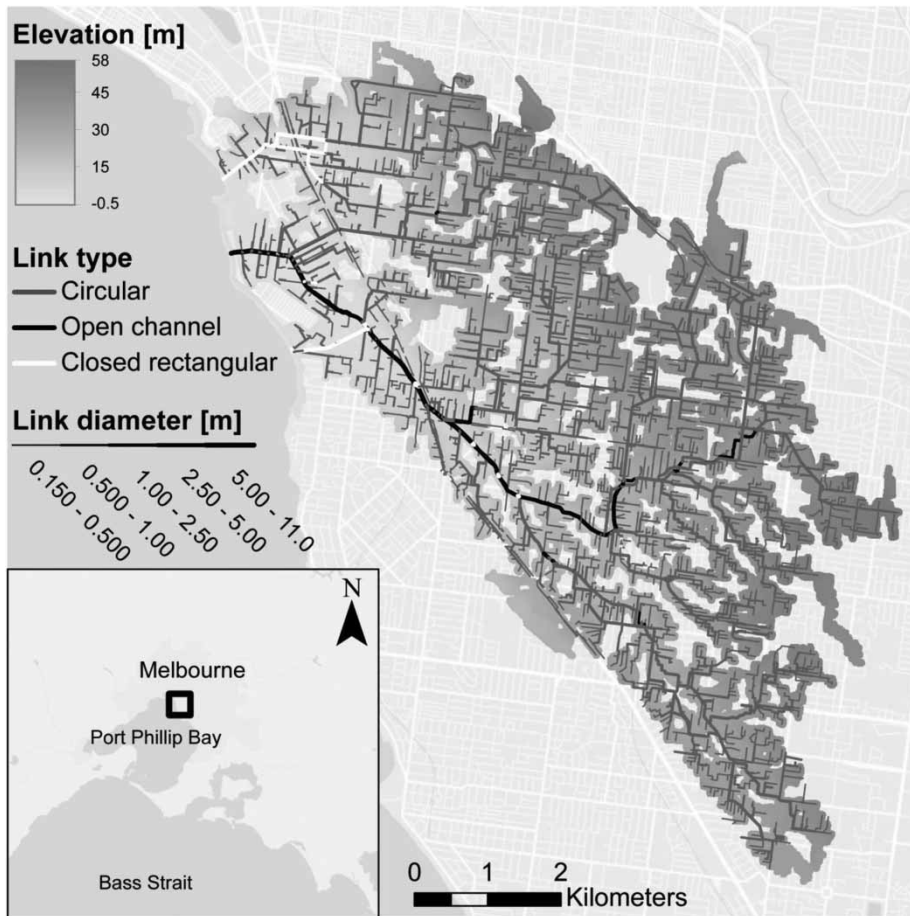
Figure 3 │ Skeletonised drainage network and elevation of the case study area in southern Melbourne, Australia.

been implemented in these models. As a measure of the level of simplification, we use the network reduction factor, *NRF*:

$$NRF = \frac{\text{Elements in simplified model}}{\text{Elements in baseline}} \qquad (7)$$

The 2D surface model is identical for all 1D/2D models, hence changes are only applied to the 1D network.

Simulation environment

The simulations were conducted using the MIKE FLOOD Message Passing Interface (MPI) limited to 7 threads on a HP EliteDesk 800 G2 TWR with Intel i7-6700 3.40 GHz CPU and 16 GB RAM.

RESULTS

Computation time

In Figure 4, average computation time for the five rain events is shown for each considered model. The overall computation time decreases with the *NRF*. The computation time for 1D calculation and data management decreases while the 2D calculations require the same computation time throughout the different model setups. For the baseline scenario, the simulation time is 16.6 minutes for the 1D model, 17.9 minutes for the 2D model and an additional 11.5 minutes for data management, combining into 46 minutes. Data management consists of MPI-processes and loading/saving results between time-steps. The computational demand for data management decreases when simplifying the model as a result of smaller

Table 2 │ Model data for baseline and simplified hydraulic 1D network models

Model	Links	Nodes	Total length of links	Network reduction factor
Baseline	10,415	10,011	477 km	1.00
Merged				
TxxxM035	9,421	9,017	477 km	0.90
TxxxM050	8,596	8,192	477 km	0.82
TxxxM075	7,832	7,428	477 km	0.75
TxxxM100	7,466	7,062	477 km	0.71
TxxxM100-NC	7,466	7,062	477 km	0.71
Trimmed				
T300Mxxx	8,857	8,469	412 km	0.85
T400Mxxx	6,938	6,576	332 km	0.66
T500Mxxx	5,551	5,230	277 km	0.53
T500Mxxx-NC	5,551	5,230	277 km	0.53
Trimmed and subsequently merged				
T300M035	7,998	7,610	412 km	0.76
T300M050	7,317	6,929	412 km	0.70
T400M050	5,597	5,235	332 km	0.53
T400M075	4,724	4,362	332 km	0.44
T500M075	4,416	4,095	277 km	0.42
T500M100	3,642	3,321	277 km	0.34
T500M100-NC	3,642	3,321	277 km	0.34
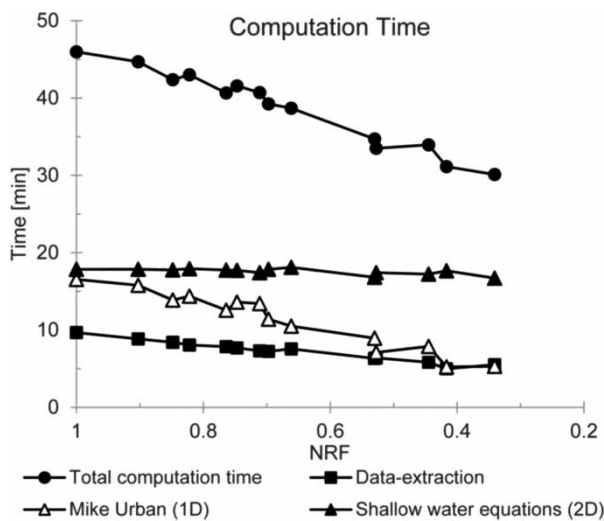
Figure 4 │ Computation time of the baseline and simplified models. The computation time depends on the number of model elements, hence the network reduction factor (NRF) is used for the horizontal axis. The computation time decreases with the number of elements in the 1D hydraulic network model due to both faster 1D calculations and fewer data to load and save during simulations. The 2D computation time is constant for all models.

file sizes. Using SAHM, the computation time of the coupled 1D/2D simulation is decreased by up to 35%. The computational effort for the 1D simulations only is decreased by 68%. The reduction in computation time of the 1D hydraulic network model thus provides a significant overall decrease in computation time for the 1D/2D flood model. With a higher resolution 2D surface, the 1D simulation will account for a smaller part of the overall computation time and hence the reduction will be less significant than in the case presented here.

1D hydrographs

Hydrographs from the 1D hydraulic network model are inspected to locate potential changes in flow characteristics after simplifying the network.

Four examples are shown in Figure 5(a)–5(d) at different locations in the network. Along main branches in Figure 5(a)–5(c), the flow is over- or underestimated, thus higher or lower volumes are transported in the network. In particular, the merged models lead to overestimation of the flow capacity of the 1D network. An explanation might be the reduction of head-losses from manholes, leading to lower energy losses. A strategy to compensate for this phenomenon may be decreasing the Manning number of the remaining links to compensate for the reduced energy loss. However, the explanation may also be that the removal of nodes in low-lying areas may lead to higher pressure gradients because there is no communication with the surface to reduce the pressure in the links.

The hydrographs for an upstream link (Figure 5(d)) suggest that the simplified models slightly overestimate peak flows while the timing of peaks varies slightly. The TxxxM100 model is delayed by a minute while the T500Mxxx and T500M100 models peak a few minutes early. The time variations are smaller than in the models without compensations (not shown), thus the time compensation works as intended with improved fit of the initial peak to the baseline even at places where trimming has removed a large part of the network. The Manning equation, used for calculation of the time compensations, describes flow processes in a more simplified manner than the Saint-Venant equations, leading to the small variations in peak time. After 2–4 hours of the simulation period, the flow is
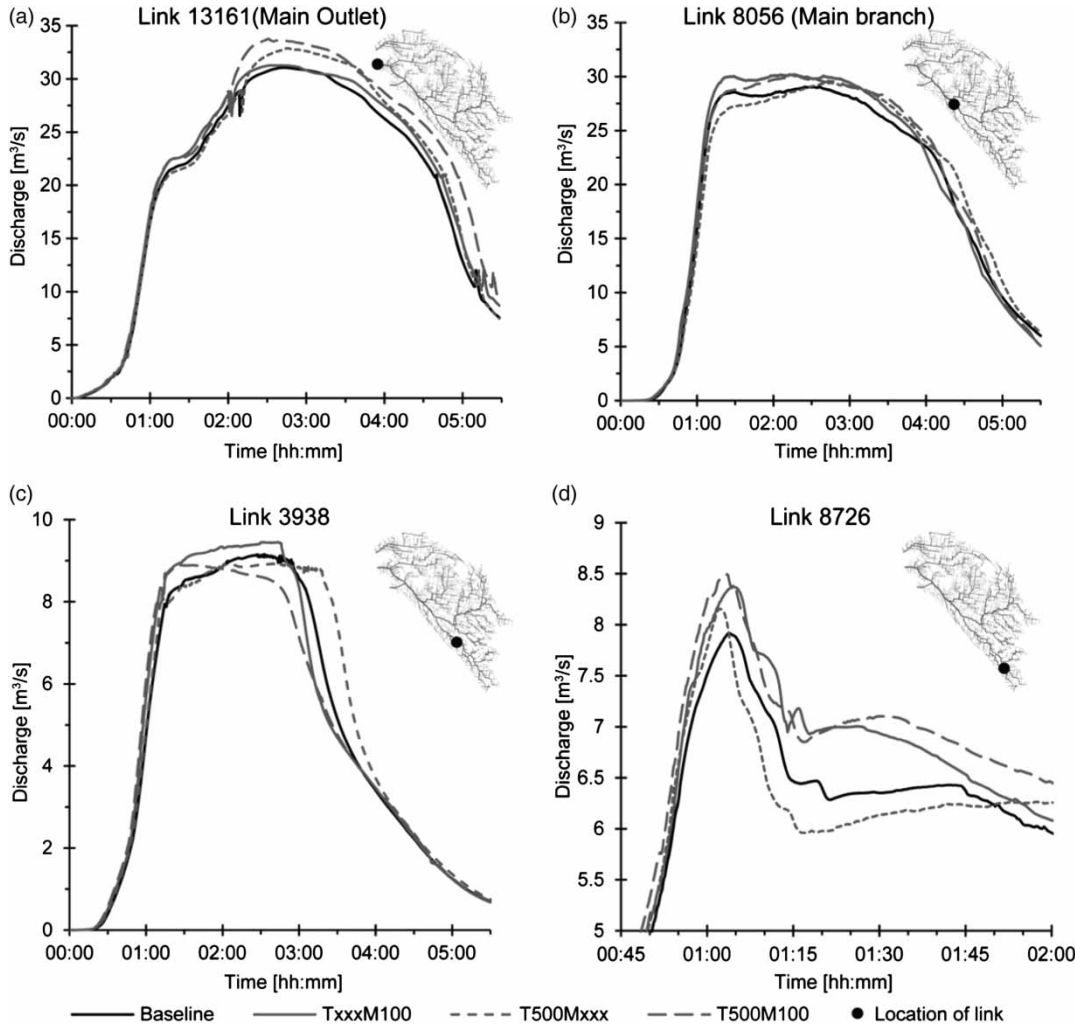
Figure 5 │ Hydrographs from the 1D hydraulic network model at a return period of 20 years for the baseline and most simplified models of the three approaches. The location of each link is indicated by a black dot on the small map in the top right of each sub-figure.

in many cases not as accurate with the decline starting earlier or later than the baseline. This may also be caused by changes in the surface flooding when storage and flow-paths change from the baseline.

1D/2D water exchanges

The outflow volume from the 1D network to the 2D surface models is illustrated in Figure 6 for 2-, 5- and 20-year return periods. For the 2-year return period, the volume exchange shows substantial increases when merging is applied, with up to 380% exceedance of the baseline. The actual volume exchange is small compared to the 10 to 100-year events, because for these events all

the volume in the 1D model is fully utilised. Simplifications of the 1D network then have only little impact on the simulated surface flooding. For larger return periods, there appear to be no differences between trimming and merging of the models. However, for return periods up to 10 years the results indicate that merging is more important for the combined 1D/2D model result because the removal of (downstream) nodes may lead to higher pressure and hence a higher water exchange with the surface of the model. This tendency is exclusively observed in models compensated for volume losses, while non-compensated models (not shown in Figure 6) maintain water exchanges similar to the baseline. Increasing the node diameter thus significantly affects the water exchange
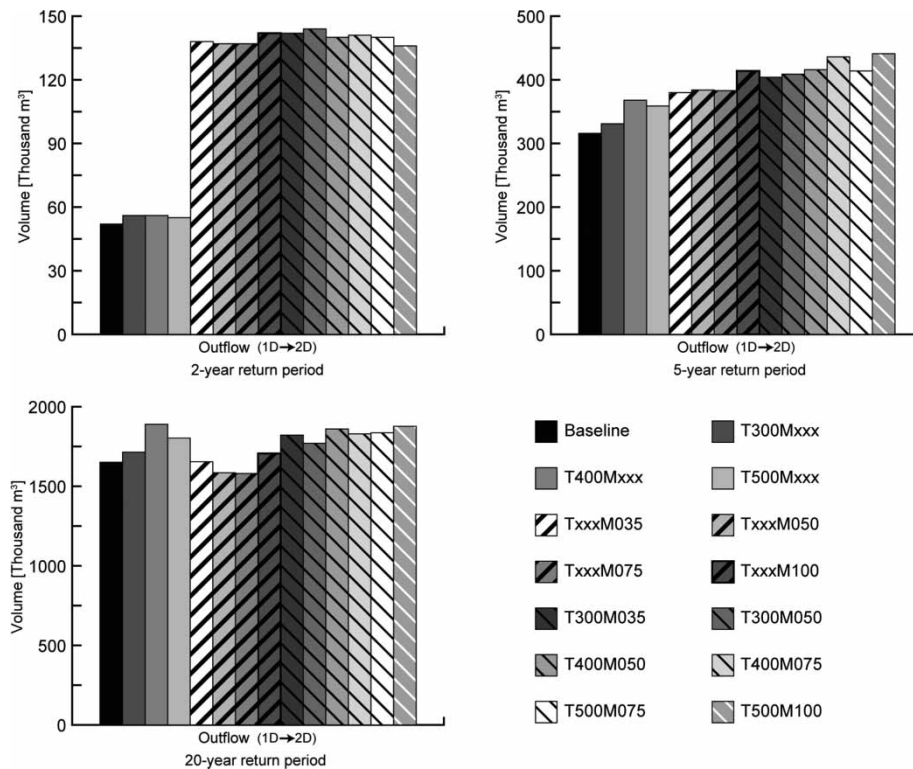
Figure 6 | Water outflow from 1D network to 2D surface for return periods of 2, 5 and 20 years. Please note the different vertical scales.

calculated by the orifice equation and leads to larger water exchanges.

Except for overestimation of the volumes of the merged models for low return periods, there are no general tendencies to observe with respect to the amount of simplification. For some return periods, higher degrees of model simplification lead to smaller changes than lower degrees of model simplification and vice versa.

Spatial distribution of the model errors on the surface

The impacts of simplification in the 1D network model on the 2D surface results are presented in the following section.

In Figure 7, the flooded surface area is shown for each return period as well as the baseline variation describing the inherent uncertainty of urban drainage calculations (Arnbjerg-Nielsen & Harremoës 1996; Hansen & Liu 2004). All simplified models underestimate the flooded area for all return periods. However, the changes are small compared to the baseline variation. The maximum water level of the reduced models is lower than the baseline for return periods of 2–20 years, but higher for the return

period of 100 years despite showing similar tendencies on 1D/2D water exchange as the 20-year event in Figure 6. With increased water volumes on the surface, the results show that intensity of flooding has increased at places where flooding is already occurring. Meanwhile as seen in Figure 8, other areas are no longer flooded since they are no longer connected to the pipe network. In spite of rather accurate hydrographs in the 1D model, the spatial location of the nodes relative to depressions has a large effect on the flooding simulated in the 2D surface model.

The difference in spatial distribution of flooding is illustrated in Figure 8 as spatial hits, misses and false positives for the most simplified models, along with the maximum water depth of the baseline during a 100-year event. As shown in Figure 8(b)–8(d), the trimming approach may cause deletion of connections in locations where the full 1D model surcharges, whereby the water will surcharge at the nearby branches in the reduced model. The merging approach also leads to changes in the spatial distribution of flooding but to a much lesser extent than trimming.

Figure 9 shows the CSI, summarising hits, misses and false positives for the simplified models. All values are
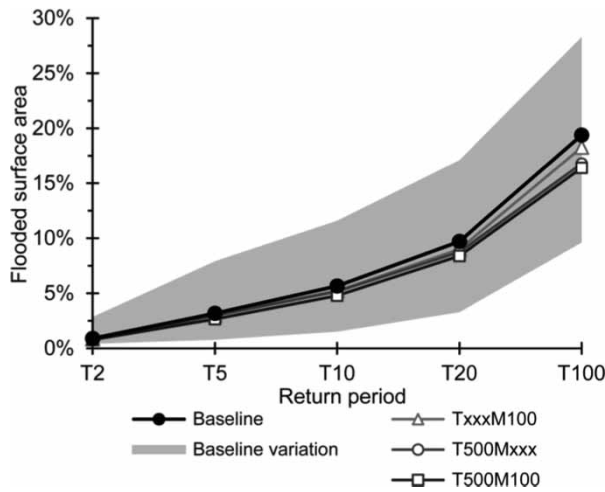
Figure 7 | Flooded surface area as percentage of the total area of the mesh. The simplified models all underestimate the flooded area but do not exceed the reference variation computed via a 23% change in runoff from Hansen & Liu (2004).

relative to the baseline and calculated as average overall simulated return periods. The errors increase as the network reduction factor decreases. The most simplified models maintain a hit-rate of 57%, while misses and false positives are around 43% and 33%, respectively. In general, the trimming approach causes larger spatial errors than the merging approach, even though the mass balance indicates that merging has the highest impact on the water exchange. Errors frequently occur in the outermost branches where trimming removes the connection to certain areas that may be flooded. Additionally, more severe flooding is simulated along main branches in all of the simplified models. Increased flooding along main branches implies a higher inflow from the smaller branches upstream, potentially linked to neglected energy losses in the removed features of the system and reduced storage of water on the surface in upstream areas.

This indicates that flooding may have moved from one location to another. This is also visible in Figure 8 where flooding in trimmed models occurs downstream in the larger branches instead of the outer branches. Inspection of the simulations shows that the spatial changes are, in many cases, limited to distances of a few pixels, hence these errors may be of little importance for many applications. This is tested by calculating the costs of flooding for a range of return periods and by calculating the *EAD* using the approach presented by Olsen *et al.* (2015).

The total damage cost for each return period is shown in Figure 10, including the variation resulting from the reference. The simplified models are very similar to the baseline for the return periods of 10–100 years while cost for the 2- and 5-year return periods are underestimated, especially for models including trimming up to a diameter of 500 mm.

In Figure 11, we see significantly lower errors in the *EAD* than the 55% change in *CSI* in Figure 9, thus supporting the hypothesis that spatial changes have a smaller impact on the catchment-wide risk. As for the flooded area, the simplified models have a tendency to underestimate the costs of flooding and higher degrees of simplification lead to larger errors. The differences in error are not the same for merging and trimming, with the merging approach leading to much lower error in *EAD* than trimming. To maintain accuracy, trimming should only be applied when merging cannot simplify the model sufficiently, thus a combination of trimming and merging should be used instead. The changes in *EAD* are generally small compared to the uncertainties of the parameters used in the cost function (Merz *et al.* 2010). Additionally, the impact of the differences in *EAD* will be further reduced in the many applications where it is the difference in *EADs* between different measures that is used as a decision-making criterion. Hence, the accuracy of the *EAD* appears to be sufficient for decision-making even for very simplified models.

Effects of compensations

The influence of the implemented compensations is investigated for all three approaches to validate if the compensations improve the results.

Including compensations for volume loss kept the total network volume deficit within 0.2% compared to 6% in the non-compensated T500M100 model.

In the 1D hydrographs, the peak arrival time and peak flow obtains a better fit to the baseline in the compensated models. In non-compensated models, the initial peak arrives earlier than in the baseline and compensated models, hence the approach for time-compensation is working as anticipated.

Despite a network volume deficit of 4.3% and 5.5% for the non-compensated T500Mxxx and T500M100 models, respectively, the 1D/2D water exchange values are better
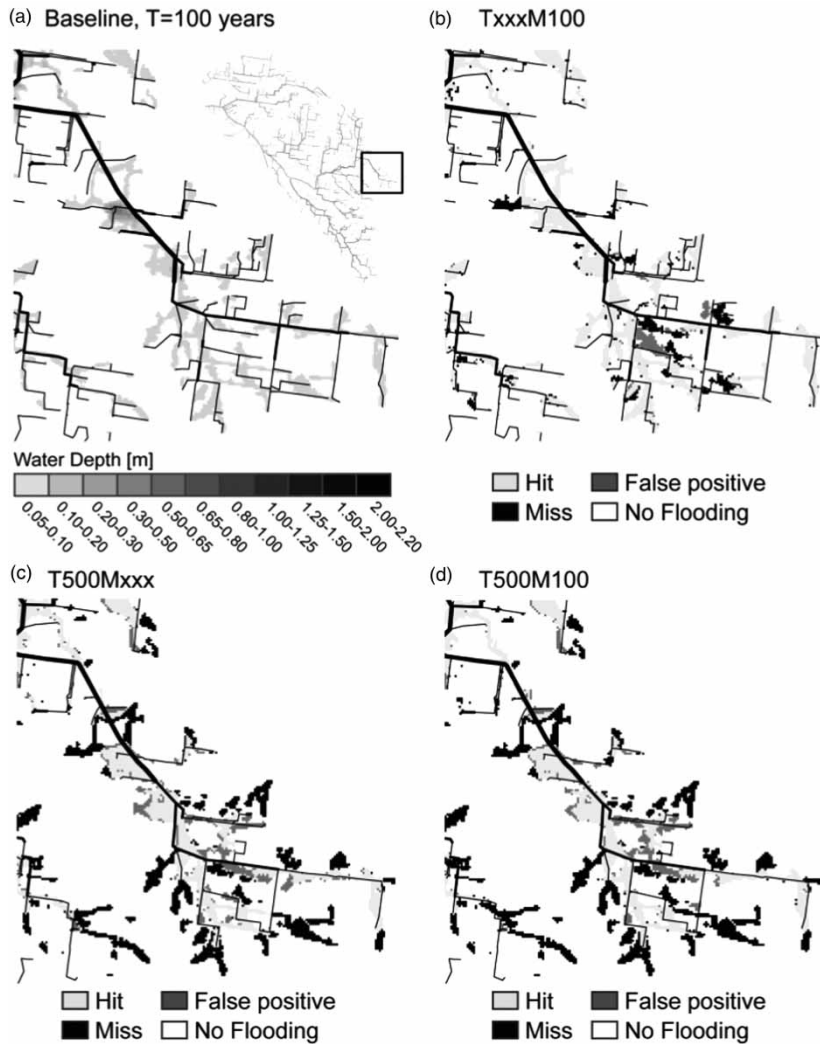
Figure 8 │ (a) An overview with the maximum water depth for the baseline during a 100-year event. (b)–(d) The differences from the baseline in spatial flood results for the TxxxM100, T500Mxxx and T500M100 models, respectively.

when neglecting the volume compensations. Additionally, the non-compensated TxxxM100 model yields similar or improved hydrographs as compared to the compensated model. Thus, it is likely that the manhole size has a more significant effect on the 1D/2D interactions than the network volume deficit and it may be beneficial to use a different approach for implementation of volume compensations, or to simply avoid the compensation scheme.

The spatial errors of the non-compensated models are shown as black symbols in Figure 9, and indicate that compensations for volume losses and travel time are of little importance for the spatial flood distribution. In Figure 11, compensations slightly improve *EAD* in the TxxxM100

and T500M100 models while *EAD* for T500Mxxx is worse than the T500Mxxx-NC model.

Overall, the compensations improve the results of the 1D hydrographs and flood area. However, compensations have only slightly positive or a negative effect on results of water exchange, *CSI*, total damage cost and *EAD*. Only when applying the compensations, outflow from the 1D network to the 2D surface varies significantly from the baseline. However, the inflow from the 2D surface to 1D network increase or decrease correspondingly with the changes in outflow, resulting in a net decrease in flooded surface area.

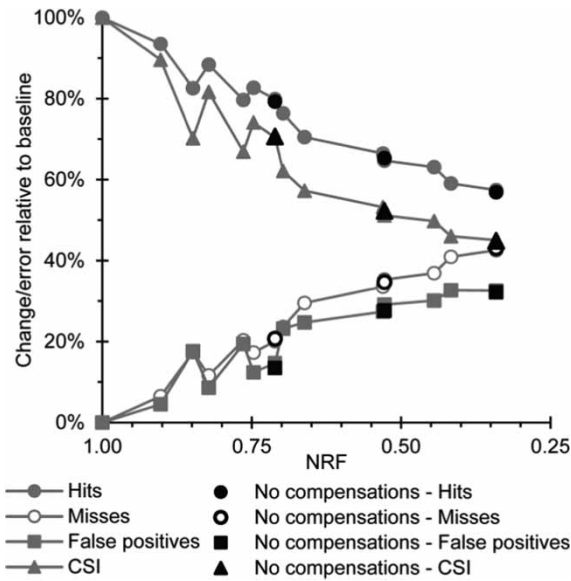When accurate hydrographs are of high priority, compensation for travel time may be justified. The small

Figure 9 │ *CSI* of simplified models along with hits, misses and false positives. Hits and misses add up to 100% while false positives are excess pixels. Models without compensations are shown with black symbols for comparison.

Figure 11 │ Changes in *EAD* from the baseline of 25.1 million AUD for each of the simplification approaches.

changes in travel time however have little effect on 2D results. Compensating for volume loss by changing manhole diameters is also not recommended as this leads to decreasing accuracy of the 2D model results.

Figure 10 │ Total damage costs of flooding for selected models. The baseline variation indicates the variation of the costs by changing the runoff only, i.e., the uncertainty of the valuation of the damages is not included.
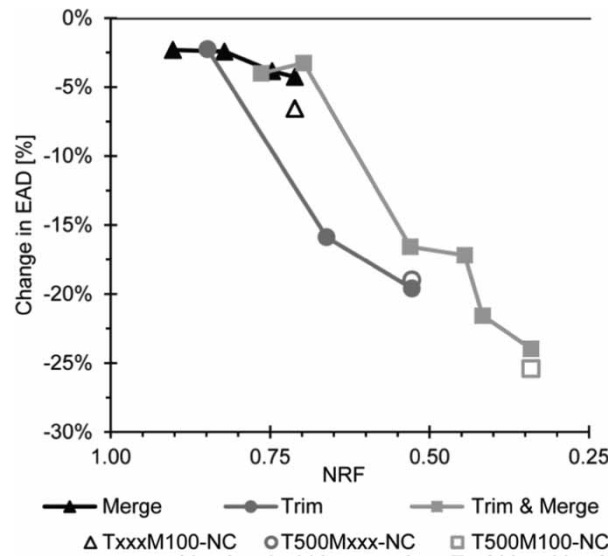
DISCUSSION

It was possible to reduce the computation time of 1D/2D simulations by 35%, exclusively by modifying the 1D hydraulic network model. The overall resulting calculated *EAD* changed remarkably little even when applying quite aggressive model simplifications. However, other metrics varied systematically as a function of the model simplification. Hence, the type and degree of model simplification that can be justified seems to depend on what the model is used for.

Even though the calculated hydrographs overall showed good agreement for different levels of simplification, the simplifications proved to have an impact on the 1D hydraulic network. The main change was identified as an overestimation of flow along main branches, occurring mostly when applying merging. The effect may be reduced by increasing energy losses, e.g., by decreasing Manning numbers, where features have been deleted.

The simplification of the 1D network model also influenced the exchange between the 1D and the 2D parts of the model, mainly for trimmed models. In general, this led to fewer locations with floods but larger flooding at these locations. This cancellation of errors is the main reason why the overall *EAD* seems to be rather accurate in spite

of a high degree of model simplification. However, for moderate return periods there will be rather large and systematic differences in the spatial distribution of flooding in the catchment. Since flooding during events with small return periods constitutes a large part of the overall risk, the degree of simplification of the 1D network is important in identifying potential measures to reduce the risk. Hence, the impact of 1D model simplification seems to have the potential of reducing calculation times considerably, but at the expense of less knowledge of where in the catchment the flooding occurs for smaller return periods.

Studies could be undertaken to see whether including features of the 2D model in the simplification in the 1D model would lead to better results. The starting point could be to put constraints on simplifications close to and in local depressions. For merging, it could be hypothesised that the key would be to include nodes in the depressions, whereas for trimming it might be important to retain links to areas with depressions.

CONCLUSION

In this study, a simplification algorithm for 1D hydraulic network models (SAHM) is developed as an automatic simplification approach. The resources spend on model simplifications are substantially reduced compared to manual or semi-automatic procedures. Additionally, the procedures are streamlined between users, with a common set of checks conducted prior to removal of a link or node. A guideline of inputs to SAHM, e.g., thresholds depending on the modelling purpose, may be an advantage to avoid over- or under-simplified models. This may be an advantage even when employing only 1D models. However, in our case, the main focus is on how such simplifications impact simulations of pluvial flooding.

The simplification of a network with more than 20,000 elements is conducted within a few minutes using merging, trimming or a combined simplification method. Using the developed approach, the computation time for the 1D/2D simulation decreases by 35% after removing 66% of the elements in the 1D hydraulic network model. The simplified models are compensated for volume losses and travel time differences. The approach of implementing compensations

for travel time leads to small improvements in 1D hydrographs of the hydraulic network model while compensating for volume losses of deleted features leads to a decline in accuracy of *CSI* and *EAD*.

1D hydrographs of the hydraulic network model show little variation between the baseline and simplified models but overestimation of flow in main branches. Spatial deviations of the 2D flood models are evaluated using the *CSI* and indicate that these models are highly influenced by the level of detail of the 1D hydraulic network. Thus, it is necessary to exercise caution when using simplified 1D/2D urban flood models for flood hazard assessments and design purposes. Calculation of the *EAD* is considerably less sensitive to model simplifications, with merging considerably more accurate than trimming. Suggestions for how the procedure can be improved further are given. For instance, maintaining connection to depressions may be a main objective to improve the accuracy of the reduced model. Overall, it already seems feasible to be able to derive simpler flood models without compromising the accuracy in an unacceptable manner.

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