A semi automated simplification method for hydrodynamic sewer models

Une méthode de simplification semi-automatisée pour les modèles hydrodynamiques de réseaux

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RÉSUMÉ

Dans la littérature récente, plusieurs approches pour la simplification des modèles hydrodynamiques sont traitées. L'objectif de cette étude est d'examiner la possibilité d'établir une procédure semi automatisée assez simple et robuste, capable de simplifier la structure hydrodynamique des réseaux d'assainissement dans la mesure où le temps de simulation et la précision sont dans une portée acceptable. La procédure finale développée suite à cette étude est présentée dans l'article suivant, dans le but de poursuivre une discussion. Une première application pour deux réseaux d'assainissement de taille moyenne dans une étude de cas a révélé que la procédure développée a le potentiel de simplifier les modèles hydrodynamiques arbitraires et de fournir des modèles très précis. Le temps de simulation est réduit à environ 30 %. Les simplifications manuelles peuvent être plus efficaces en termes de temps de simulation ; l'effort nécessaire, cependant, est extrêmement important. Par conséquent, la procédure semi automatisée présentée représente un bon compromis entre l'effort pour le modélisateur et le gain de temps de simulation. Le gain de temps de simulation dépend largement du potentiel de simplification des modèles et de la stabilité de la simulation.

ABSTRACT

In recent literature, several approaches for the simplification of hydrodynamic sewer models are discussed. The aim of this study is to investigate whether it is possible to establish a rather simple and robust semi-automated procedure capable of simplifying the structure of arbitrary sewer networks to an extent where both simulation time and accuracy are within an acceptable range. The final procedure developed from these investigations is presented in the following paper for further discussion. A first application to two sewer networks of moderate size in a case study revealed that the developed procedure has the potential to simplify arbitrary hydrodynamic sewer models producing very accurate models. The simulation time is reduced down to about 30 %. Manual simplifications can be more efficient in terms of simulation time; however, the effort they require is exorbitant. Therefore, the presented semi automated procedure represents a good trade off between effort for the modeller and gain in simulation time. The gain in simulation time vastly depends on the models' potential for simplification and the stability of the simulation.

KEYWORDS

Sewerage system, hydrodynamic modelling, sewer model simplification

1 INTRODUCTION: EXISTING SIMPLIFICATION METHODOLOGIES

1.1 General possibilities of simplifications

The goal of model simplification is usually the reduction of computational efforts. The choice of a certain simplification method will in most cases be influenced by the foreseen purpose of the simplified model. Potential applications for simplified models include long term simulations, integrated modelling or, as presented in this paper, scenario analyses for adaptation measures such as real time control.

The most simplistic means of sewer modelling is represented by static volume balancing methods such as the “method of Kuipers” (e.g.: Berlamont, 1997) or “Entlastungsgrenzlinie” (Xanthopoulos, 1990). The capabilities of these static methods to model the dynamic behaviour of sewer systems is very limited, their accuracy thus usually unsatisfying (Kroll et al, 2007).

One very common way of simplifying hydrodynamic models is to replace them by so called conceptual or hydrologic models that lump big parts of a sewer network into a very limited number of modules and describe the processes by partly physically based relations. This simplification allows for distinctively faster simulations than in detailed hydrodynamic models. However, these models usually require extensive calibration to deliver accurate results. To gain sufficient data for such calibrations it has proven very valuable to make use of data stemming from hydrodynamic models (e.g.: Meirlaen et al, 2001, Vaes et al., 2002).

Another possibility of simplification is to modify the solution algorithm that is used to produce results for hydrodynamic models. Instead of solving the full St.-Venant equations it can be beneficial to only use a part of the equations if the hydraulic situation allows to neglect certain physical details. Well known examples are the diffusive and kinematic wave approach. These are not able to accurately simulate complex hydraulic behaviour such as backwater effects. Also the solution algorithms proposed by Motiee (1996) or Kalainin-Miljukov (e.g.: Engel, 1997) can be seen as substitutes to the St.-Venant equations since they combine the basic ideas of conceptual modelling with the detailed network structure of detailed hydrodynamic models.

Refraining from replacing the entire modelling environment or using a substitute for the solution algorithm, the here presented work focuses on the possibilities of structural simplification of existing hydrodynamic models.

1.2 Structural simplifications within hydrodynamic models

Scientific literature provides insight into a number of already existing procedures for the simplification of hydrodynamic sewer systems. We here discuss the ones that had an influence on the development of the suggested semi-automated procedure. By their nature, these methods can be distinguished into procedures that rely on entirely manual modification of the model and procedures that partly make use of computer based algorithms.

1.2.1 Manual approaches

Fischer et al (2009) and Rouault et al (2008) discuss two case studies that were carried out to investigate the possibilities of manual simplification of hydrodynamic models. There, the modeller takes decisions based on personal experience and/or simulation results in order to decide whether a certain region of a network is of crucial importance for accurate simulation results or if this part of the system can be simplified. Aside from a number of boundary conditions, there are no specific criteria to be met in order for a group of pipes to be considered for a simplification. Usually, conduits that form a side branch to the main collector are subject to simplification. Fischer (2006) and Fischer et al (2009) discuss two major levels of simplification when removing side branches from a part of the sewer network:

1. If a simplification seems possible for a certain part of the network, **all conduits and nodes in this region are removed**. Only the conduit connecting this region to the rest of the sewer network remains. The loss of storage is accounted for in virtual volumes at the upstream end of the remaining conduit. The results of this approach were not satisfying when simplifying the entire sewer network. For small regions within a detailed network, however, this procedure can yield acceptable results (Fischer, 2006).
2. Since the reduction of the entire network into a couple of pipes and virtual storage units did mostly not result in sufficient accuracy of the network, it was decided to **leave the main collectors in the network and only remove side branches** (Fischer et al 2009). Figure 3

gives an idea of a comparable procedure. The decision, which branches of the network remain in the network is here again based on the modeller's experience and the hydraulic behaviour of the system.

Further tests where it was tried to reduce the number of runoff areas by merging them and recalibrating their parameters did not yield the desired effect (Fischer, 2006).

As a result of removing side branches of lower importance from the network the simulation time could be reduced to about 36 %. The volumetric error of the most downstream network element was about 1 % (Fischer et al 2009).

Several locations of the case study discussed by Fischer (2006) required modifications that were specific to these respective locations. This is an indication that the procedure developed there might not always be applicable to arbitrary sewer network structures.

Another approach for the simplification of hydrodynamic models is discussed by Rouault et al (2008). The major difference to the formerly discussed methods is that **all pipes of a certain region of the network are replaced by a couple of synthetic pipes** that represent the most important characteristics of all conduits in the region under consideration. The pipes of one region are grouped by their distance to the most downstream point of that region, where the relation of these pipes to each other is of no importance. The one group can thus contain conduits that are in parallel and at the same time others that are in series to each other. Each of these groups of pipes is replaced by one single pipe that has the same storage characteristics and the average slope of the group. Parameters of the pipe are calibrated by a manual trial and error optimisation (Rouault et al, 2008). The runoff areas belonging to one pipe group are connected to the upstream end of the according newly created pipe. Also their runoff characteristics are optimised by trial and error. Figure 1 shows the modification of a network according to this simplification methodology. As can be seen, almost the entire network structure is modified.

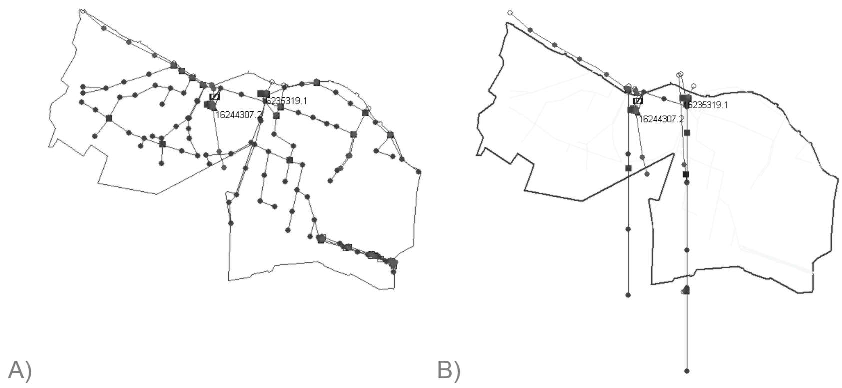

Figure 1: Original (a) and simplified network (b) by Rouault et al (2008)
(taken from Fischer et al, 2009)

For the simplification of the here shown network Rouault et al (2008) report a reduction of the simulation time down to 41 % entailing a deviation of CSO discharge volume of 4 %.

1.2.2 Semi automated approaches

Two semi automated approaches are recently discussed in literature. Schindler et al (2007) propose a procedure that is based on a number of criteria: the conduits that are considered for simplification have to show comparable characteristics regarding slope, shape and size. The length of the created merged pipe may not exceed a certain maximum. All control devices and ancillary structures (e.g.: pumps, storage basins, sluices etc.) are excluded from simplification. In addition to the sewer network structures, also catchment areas with resembling characteristics can be merged into one. Links that are separated by an invert offset are excluded from simplification.

The main focus of this way of simplification is on **merging of several reaches in series into one single reach**. Figure 2 illustrates this. First, the network is searched for potential groups of pipe reaches in series that comply to the simplification criteria, e.g.: the tolerance in conduit diameter deviation of consecutive pipes (A). All pipes that are found suitable for simplification are removed from the network and replaced by one single conduit whose characteristics are derived from the structural data of the removed pipes. The runoff areas that were linked to any of the manholes in the simplified reach are reconnected to manholes that still exist after the simplification (B).

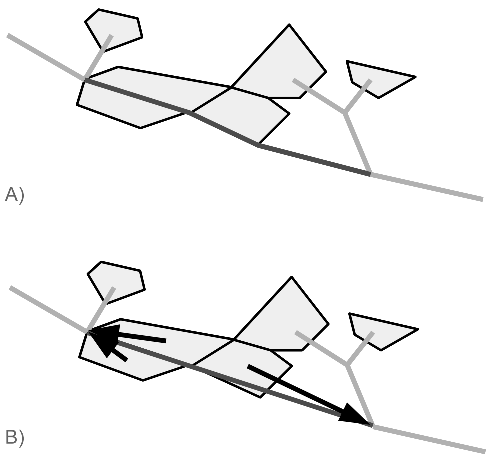

Figure 2: Simplification by merging several pipe reaches in series into one

Applying this procedure to a test catchment, the number of links is cut down to 50 % reducing the simulation time by the same factor. The high accuracy of the produced simulation results leads the authors to the conclusion that the tested network still holds potential for further simplification (Schindler et al, 2007).

As opposed to this first approach that focuses on the merging of consecutive pipe reaches, the procedure proposed by Kroll et al (2010) **eliminates side branches in a sewer network** which are of low importance to the overall simulation results. This is demonstrated in Figure 3.

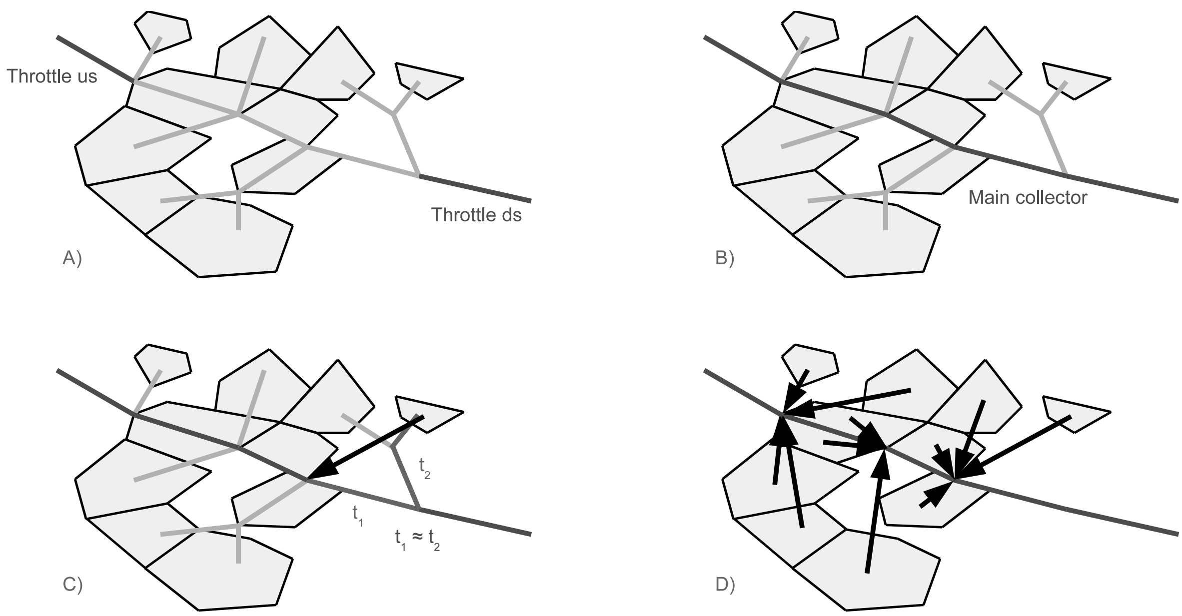

Figure 3: Simplification by side branches

Comparable to the manual approaches, several regions of a sewer network are simplified on their own. First, all structures that delimit such a sub basin are identified (A). These can be weirs and throttles as they have already been defined for the separation of sub basins but also additional points of attention declared as such by the modeller. For all these points, a search algorithm derives a series of consecutive links that leads to the downstream throttle of the sub basin to be simplified (B). These series of links form the main collectors that will remain in the simplified sub basin. All links and nodes that are not part of these collectors will later be deleted from the network. The runoff surfaces connected to these side branches will be reconnected to manholes that form part of the main collectors. This is done in step C) of the simplification: For each runoff surface the travel time of the water to the next downstream throttle of the sub basin is calculated. The travel time for each manhole in the main collectors is determined accordingly. The runoff surfaces are now connected to the respective main collector manhole with the best fitting travel time. This method can be seen as a detailed interpretation of the well known time area method (e.g.: Achleitner, 2006). After all runoff surfaces have been assigned to a manhole on the main collector, the obsolete side branches are deleted from the network (D). To compensate the loss of storage volume caused by the removal of these branches, an equivalent virtual storage volume is introduced to the last downstream manhole of the main collector. The shape of these “storage nodes” corresponds to the static storage behaviour of the deleted branches. The loss of transport capacity remains unconsidered in this approach.

When being tested on a case study, this algorithm was able to reduce the number of pipe reaches in a network down to about 30 %.

1.3 Comparison

Comparing the different procedures here briefly introduced for the structural simplification of sewer models it can be stated that the procedures that involve an entirely manual build-up of the simplified models have the advantage that the modeller can take “engineering” decisions for each location that is to be simplified. The trial and error calibration that is part of both approaches can ensure highly accurate simulation results. However, the exact reproduction of manually simplified networks cannot be guaranteed since the simplification is vastly based on assumptions and personal experience of the modeller. Also the time consumed for the simplification might not always be justified. Both authors of these procedures consequently propose an automation of the simplification process.

Also the semi automated build-up yields highly accurate results but shows rather low impact on the simulation time. However, the two algorithms reviewed here are complementary by their nature: while one focuses on the elimination of less important side branches, the other one applies to consecutive pipe reaches. A combination of both could hence bear high potential for further reduction of the number of elements to be simulated and thus yield a further decrease in simulation time. Such a combined approach and its exemplary application to two case studies is presented in the following.

2 METHODOLOGY

The aim of this study is to investigate whether it is possible to establish a rather simple and robust semi automated procedure that is capable of simplifying the structure of arbitrary sewer networks to an extent where both simulation time and accuracy are within an acceptable range. The final procedure that evolved from these investigations is presented in the following for further discussion.

Combining the concepts of the two previously introduced semi automated procedures, the here proposed method also relies on the manual definition of boundaries between regions that are to be simplified and the identification of main collectors. After a first simplification step according to the procedure suggested by Kroll et al (2009) as it has been described above, the remaining main collectors are in a second step subjected to a second simplification step to reduce the number of pipe reaches. In order to do so, all n consecutive pipe reaches that are purely linear are clustered into all possible combinations of $\sum_{k=1}^{n}(k-1)=\frac{n\cdot(n-1)}{2}$ groups. Figure 4 shows such a group of serial reaches and all possible combinations for $n=5$ pipe reaches.

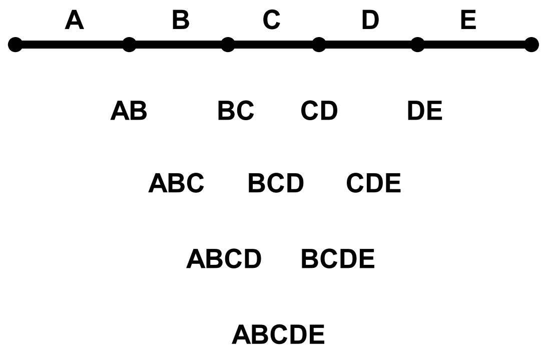

Figure 4: All possible clusters for a group of n = 5 reaches in series

For each of such derived groups the procedure calculates a score based on the following criteria:

- Tolerance of deviation of conduit dimensions of all pipes in the group
- Tolerance of invert offset between neighbouring pipes
- Tolerance of slope deviation of all pipes in the group
- Maximum total length of the pipes in the group
- Consistency in conduit shape

While an inconsistency in the conduit shape immediately discards a group of pipes (score for shape $S_{shape} = 0$), all other criteria are used to calculate an intermediate score S_{crit} based on a simple formula comparing maximum allowed tolerance and actual deviation of a criterion:

$$S_{crit} = w_{crit} \cdot \max\left(allowedTol_{crit} - deviation_{crit}, 0\right)$$ where w_{crit} … criterion specific weighing factor

The limitation to minimum values of $S_{crit} = 0$ requires specific handling of zero tolerances but allows for a simple multiplication of the scores of all criteria to determine the fitness of the group of pipes under consideration.

$$S_{tot} = \prod S_{crit}$$

After this score has been derived for each group of pipe reaches, the maximum of all nonzero values is determined. All groups that contain any of the pipes also contained in the selected group are discarded by setting their score to zero to exclude them from further simplification considerations. The group of pipes with the maximum score is merged into one pipe. This is done by deleting all conduits and manholes of this group from the network and replacing them with one single conduit. This pipe has the total length of the cumulated length of all pipe reaches and the same volume. The up- and downstream invert level of this conduit are adjusted in order to obtain an invert slope $I_{simplified}$ that is equal to the weighed average of the individual slope inverts I_k of all the conduits of the group.

$$I_{simplified} = \frac{\sum l_k \cdot I_k}{\sum l_k}$$ where l_k … length of pipe reach k

This ensures minimal impact of the simplification on the flow behaviour of the considered group of pipes. The volume of the deleted manholes is added to the already in step 1 of the procedure established virtual storage volume at the downstream end of the main collector. Finally, all runoff areas that were connected to manholes which do not exist anymore due to the simplification are connected to the remaining manholes according to their travel time to the downstream end of the main collector following the same considerations as described for step 1 of the procedure.

3 CASE STUDY

3.1 Catchment characteristics

Two sewer networks have been used as case studies to test the simplification procedure. Both form part of the greater Leuven catchment, which is situated about 30 km east of the city of Brussels in Flanders, Belgium. They both are used as test catchment for a study on the applicability of integrated modelling and Real Time Control (RTC) strategies to Flemish catchments. This study called for simplified models of the investigated area in order to keep simulation efforts on a manageable level since the measures taken here might potentially form the basis for further investigations in more than 100 other wastewater systems. The catchments cover a contributing area of about 1131 ha (297 ha impervious) and 578 ha (125 ha impervious), respectively. The combined sewage is conveyed to the central wastewater treatment plant of Leuven. Combined Sewer Overflows (CSO) are taken by several small, partly heavily modified receiving waters at 10 and 12 CSO locations, respectively. For such investigations it is indispensable to rely on sound modelling results regarding CSO activities.

Herent, the smaller of the two study sites, can be considered to show the typical properties of a Flemish sewer system: fairly small slopes, considerable influence of backwater effects on the routing process, in-sewer storage, throttle pipes instead of dedicated throttle devices, several backwards working overflows (weir separated from throttle). Kessel Lo includes most of these features but, on the other hand, shows less balanced hydraulic behaviour and is consequently used in this study to test the simulation accuracy and stability of the simplified models.

With about 1900 and 1250 sewer reaches, respectively, both models are rather small and manageable in terms of measurements and supervision in comparison to other catchments available for this investigation. This is also crucial for modelling since many long-term simulations were carried out with the models and their simplified derivates.

3.2 Results

In the scope of the here presented study the two networks have been simplified according to the 4 criteria tolerance of deviation of conduit dimensions, tolerance of invert offset, tolerance of slope deviation and maximum total length of the pipes in one group to analyse the influence of each of these criteria on the degree of model simplification and the simulation result accuracy. The choice of the main collectors – required for the first simplification step of the procedure – thereby remained the same for all modifications of the merging criteria.

Figure 5 shows the reduction of links as function of the merging criteria when being applied to the algorithm as the only limiting criterion, i.e. all other criteria are set to values that will not influence the simplification.

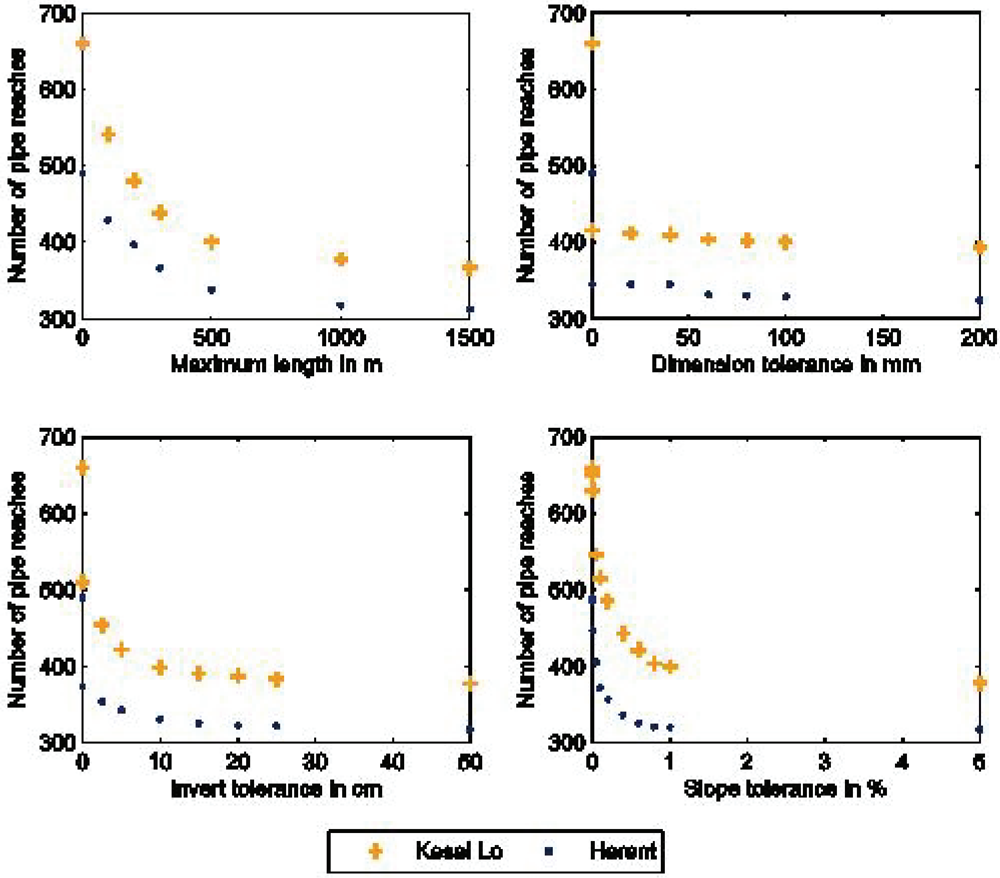

Figure 5: The influence of the applied simplification criteria on the degree of simplification shown as number of pipe reaches remaining in the model

As can be seen, the tolerance of conduit dimensions has only very limited influence on the number of links resulting from the simplification of the two tested networks. This is not surprising since most of the pipe reaches in the system are built from prefabricated conduits that are produced in standardised sizes and thus vary only with rather big intervals. The other three criteria provide better means for fine tuning the simplification degree of the resulting network. The widest range can be obtained by a modification of the maximum allowed conduit length.

The simplified models derived from the initial model of Kessel Lo have been used for a simulation of a time series of historical rain data of one year to determine the impact of the simplification on the modelling accuracy and the time required for simulation. The criterion evaluated to asses the accuracy was the error of the modelled cumulated combined sewer overflow volumes along with visual inspection of the results of the most significant model structures. In general it can be stated that the simplified models returned highly accurate results despite a reduction of the network structure by 40 % up to 80 %. Figure 6 gives an overview of the influence of the model simplification on the loss of accuracy.

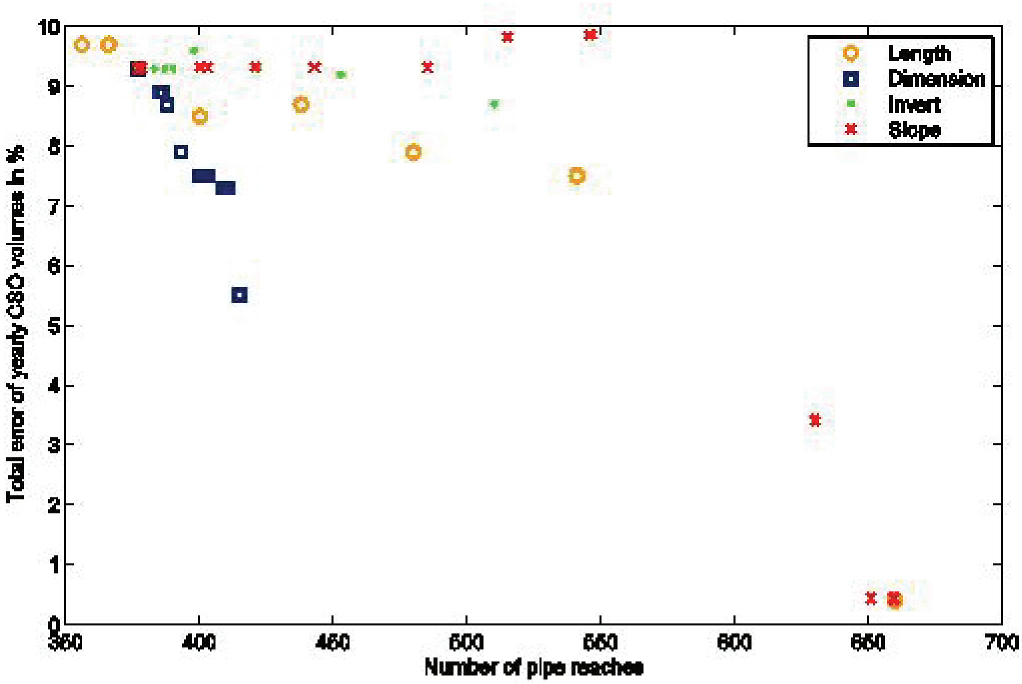

Figure 6: The influence of the degree of simplification on the modelling accuracy

It indicates that most of the criteria barely have an influence on the modelling accuracy, once they are applied to a certain extent. Exception to this rule is the tolerance of the conduit dimension to which the modelling accuracy proves to be very sensitive. As seen already in Figure 5, a zero tolerance in dimension still can allow for a reduction of the number of pipe reaches from the in step 1 reached 35 % down to about 22 %. The then occurring error of about 6 % in overflow volume can be assigned to the fact that the number of conduit entries and exits is significantly reduced, lowering the overall hydraulic losses in the system. Preliminary tests show that an adaptation of the loss coefficients can provide an efficient means to overcome this shortcoming. If the error is compensated this way, the tolerance of the deviation in conduit dimensions is the criterion of choice for a simplification via merging of pipe reaches. The results however also indicate that the correct choice of the main collectors in the network has the biggest impact on both the degree of simplification and the model accuracy: While removing side branches from the model reduces the number of pipe reaches from 1900 to 660 (i.e.: 35 %) without afflicting the modelling results with a significant error (here 0,5 %), the merging of conduits further reduces the number of pipe reaches to 380 (i.e.: 20 %) but introduces a volumetric error of about 10 %. Since, however, the definition of main collectors is a task to be done by the modeller while the merging can be done entirely computer based, a trial and error optimisation of different tolerances for the merging process can be carried out with very little additional effort.

The findings by Schindler et al. (2007) stating that the degree of simplification and the simulation time are related strictly linear cannot be confirmed by the simplified models in this case study. Figure 7 indicates that the number of links and nodes to be simulated is not the only parameter which has an influence on the simulation time in the here used models.

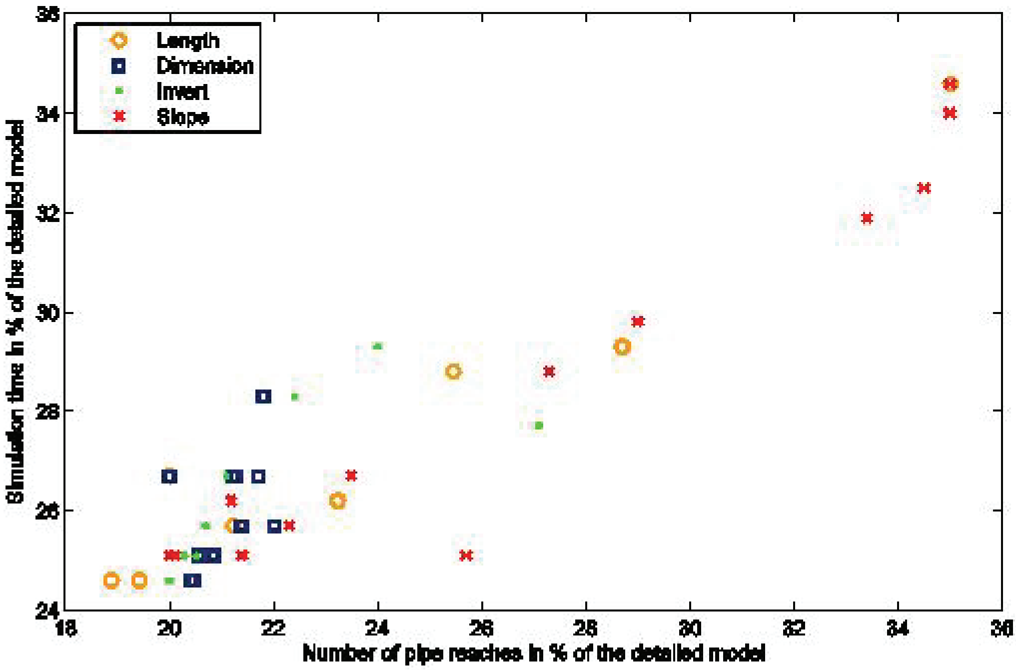

Figure 7: The influence of the degree of simplification on the simulation time

Also runoff areas and (more importantly) control structures and conduits that slow down the simulation due to problems in the numeric solution of the St.-Venant equations can have a significant impact. Single links, especially pumps, rising mains and confluents directly behind weirs can have significant influence on the overall simulation time of the model. Some of the problems arising from these structures can be overcome by careful modification or replacement of these critical structures. As this is not possible in all cases and requires considerable efforts, the tested models have not been modified with regard to such problems. As a result of this, a reduction of the number of pipe reaches to 20 % only speeds up the model by factor 4. Compared to the previously discussed methods found in literature, these results signify an overall improvement of the ratio of degree of simplification, modelling accuracy and required effort for model build-up.

4 CONCLUSION

A semi automated procedure for the simplification of hydrodynamic sewer models has been developed and tested on two networks in a case study. Simplifying the models by reducing the number of modelled pipe reaches to about 20 to 30 % caused a maximum error of the over one year cumulated CSO volume of 10 %. This appears acceptable for most modelling applications and especially for the purpose the models were initially simplified for (e.g. RTC scenario analysis).

Manual trial and error calibration procedures can in specific cases deliver a better ratio of accuracy and degree of simplification. The here proposed semi automated algorithm is thought to be a straight forwardly applicable procedure where only the selection of main collectors leaves room for adaptation of the model based on simulation results and modelling experience. This can be seen as a limitation of the automated procedures. However, their application for the buildup of simplified models requires considerably less efforts by the modeller and shifts much of the work to the automated procedure. Therefore, the presented semi automated procedure represents a good trade off between effort for the modeller and gain in simulation time.

Potential further investigations could include the application of the procedure to river models to investigate the applicability of the methodology to their significantly different structure. Given usually less branched structure of river networks, the here proposed algorithm could potentially be amended so that the required interaction of the modeller could be further reduced and the algorithm could be automated entirely. At this stage, the procedure could prove to be an interesting tool to be implemented in the environments of existing modelling software packages.

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