Large scale 1D-1D surface modelling tool for urban water planning

Un outil de modélisation de surface à grande échelle 1D-1D pour la planification de la gestion des eaux urbaines

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RÉSUMÉ

L'augmentation des précipitations due au changement climatique, associée à l'urbanisation rapide des villes peut entrainer une augmentation des inondations en zone urbaine. Des méthodes et outils simples sont donc nécessaires pour élaborer les cartes des zones à risque d'inondation dans les grandes agglomérations, ou identifier les bassins versants où une approche de modélisation est nécessaire. Ce document présente les progrès récents quant aux méthodes de dépistage des zones à risque d'inondation au moyen d'un modèle traditionnel 1D d'écoulement en réseau d'assainissement couplé à un modèle 1D d'écoulement en surface. L'idée est basée sur l'algorithme d'un logiciel GIS entièrement automatisé, tout en associant des techniques bien connues de modélisation des systèmes d'assainissement avec des techniques nouvelles décrivant l'écoulement des eaux de surface. La sensibilité du système en termes de hauteur d'eau et d'intervalle de temps a été analysée et a permis de constater qu'un seuil de hauteur d'eau de 40 cm est satisfaisant pour l'analyse, mais qu'un seuil de 20 cm donnera une information plus précise sur des hauteurs d'inondation moins importantes. La méthode présentée est un système efficace pour la planification et la gestion des systèmes d'assainissement urbain qui sont plus vulnérables aux inondations, et peut aider les services publics à mieux s'armer face aux défis du changement climatique.

ABSTRACT

Predicted increase in extreme rainfall due to climate change, combined with rapid urbanization, can lead to an increase in urban flooding. In order to create flood risk maps for larger areas or when screening catchments to identify where detailed modelling is required, simple methods and tools are needed. This paper presents recent progress in methods for flood risk screening using a traditional 1D collection model combined with a 1D surface description. The concept is based on a fully automated GIS algorithm combining known techniques for modelling of sewer flow with novel techniques describing overland flow. Sensitivity analysis on the flood threshold depth and time steps have been carried out and it was found that threshold depths of 40 cm are acceptable for screening purposes, while a threshold value of 20 cm will give more localized information on lower flood depths. The method outlined represents an efficient system for planning and management of urban drainage systems suffering from urban flooding and can help utilities prepare for the challenge of climate change.

KEYWORDS

Urban flooding, planning and damage control, large scale modeling, 1D collection system combined with 1D surface, large scale case study

1 INTRODUCTION

Predicted increase in extreme rainfall due to climate change combined with rapid urbanization can lead to increase in urban flooding. Flooding can occur as flash floods after heavy rainfall caused by inadequate drainage capacity, poor maintenance of sewage system or heavy runoff due to an increase in urbanization.

When flooding occurs overland flow tends to run on a complex terrain with many flow paths in close connection with the collection system. In recent years there have been advances in modelling the interaction between sewer models and models describing the flow on the surface e.g. (Nielsen et al, 2008), (DHI, 2010), (Deltares, 2008), (Boonya-aroonnet et al, 2007), (King, 2006), (Maksimović 2009) and (Sume, 2001),. These methods are all capable of describing complex flow across an urban flood plain. However, the work needed to implement and verify the models, are time consuming and the requirement for small time steps makes these methods inadequate for forecasting or planning for larger catchments. In order to create flood risk maps for larger areas or when screening catchments to identify where detailed modelling is required, more simple methods and tools are needed.

A number of studies on urban flooding in Denmark were completed during the period of 2005-2008 (Nielsen et al, 2008). For those studies a detailed urban flooding model (Mike Flood, DHI 2010) was used. The most important factors for the model results were identified as:

- The volume of the water from precipitation.
- The topography of local ponds and depressions.
- The level of the lowest path between the ponds, depressions and manholes.

In this paper, recent progress in methods for flood risk screening using these factors is described. The concept is based on a fully automated GIS algorithm combining known techniques for modelling of sewer flow with novel techniques describing overland flow. Recent technologies of high-resolution DTM (Digital Terrain Model) and DEM (Digital Elevation Model) e.g. LiDAR (Ligth Detection And Ranging) makes the use of terrain models for fully automated flood analysis possible (Evans et al, 2009). This paper describes the concept, testing, trial and practical application of the method developed.

2 METHODS

Most existing hydrodynamic 1D collection models have well tested and documented modules for simulating basins and weirs which is similar to the hydraulic of ponds and paths on the surface, e.g. MOUSE (DHI, 2010) or InfoWorks (Wallingford Software, 2010).

In this study a fully automated GIS based algorithm integrating a digital terrain model with a collection model was developed. Preferential surface pathways were identified using the “rolling ball” technique and a Digital Surface Model (DSM) was used as input. With a high resolution of the DSM below 2 m this would ensure that urban features such as roads and buildings to be properly described. To ensure that volumes in flooded houses would be included in the calculation of the potential flood volumes a Digital Terrain Model (DTM) was used. The difference in potential flooded areas for the two methods used is illustrated in figure 1. When using the DTM more local flood phenomenon will be neglected. This is especially important when preferential flow paths are controlled by structures in the urban environment.

Figure 1. Difference in flow paths and calculated ponding areas when using a DTM (left) or DSM (right) as input.

The collection model setup and DTM data is used as input and setup for an integrated 1D-1D model with a collection system and ponds and paths on the surface is the output. For simulating scenarios only *one* hydraulic model system is used ensuing numerical stability at the interaction between collection system and surface and correct water balance. In this study MOUSE (MOUSE, DHI 2010) were used as the hydrodynamic 1D model. Water is routed from the sewer network (incl. streams) to the surface and between ponds on the surface using a weir equation. The linking between the surface and the pipe model is illustrated in figure 2. Using weir equations to route the water on the surface is incorrect from a physical point of view but it does decrease the calculation time and memory allocation significant. The inaccuracies using this simple routing method as an alternative to a 2-D vector based method are small for short steep pathways and large for long flat pathways. For areas with long flat pathways open channels should be adapted.

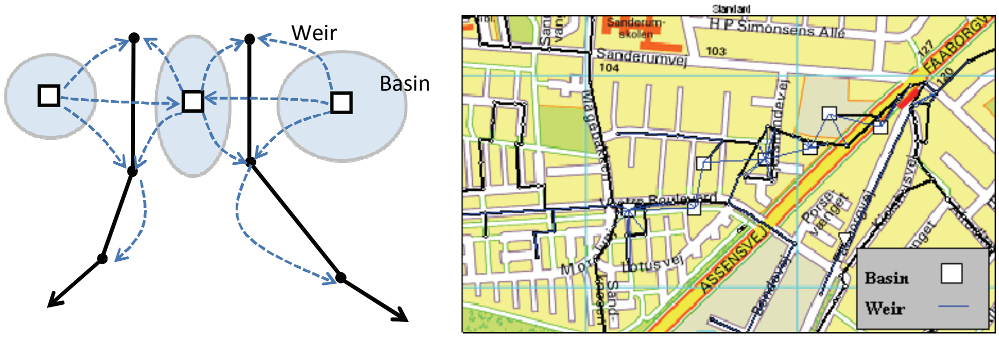

Figure 2. Linking sub catchments, preferential flow pathways, flood risk areas and manholes from the sewage network.

The developed GIS tool defines the location, the level-area curve and the topographic catchment and connection paths for each surface basin. The temporal filling of the ponds (basins) on the surface is defined using a volume function depending of the topography as illustrated in figure 3. The collection system manholes are spatially connected to the catchments and the surface basins.

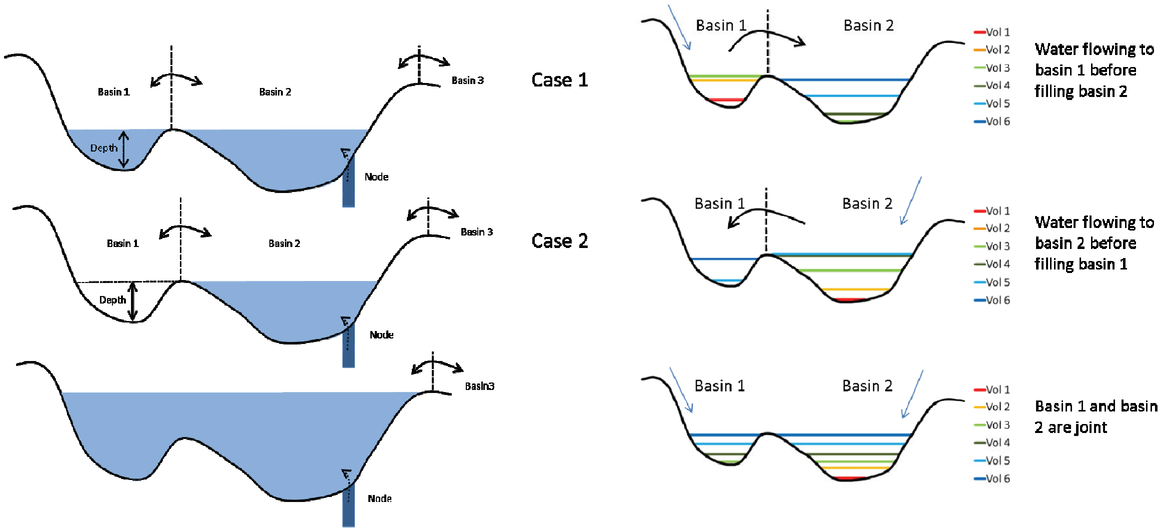

Figure 3. Volume function used to describe the temporal flooding of ponds (basins) on the surface.

In the 1D-1D screening approach it is crucial to generate as few ponds as possible without loss of essential information of flooding areas. In the GIS tool a minimum threshold depth and volume for the model basins is defined and minor basins are following merged into basins adapted in the model. This will enable the model setup to do calculations on a very large scale and leave out noise from the terrain models used.

Results are transformed from 1D to a 2D GIS presentation by linking the surface basin distribution with calculated maximum water levels for each depression.

3 RESULTS AND DISCUSSION

The model setup was tested on a large catchment in Greve, Denmark. A digital terrain model with a resolution of 1,6 m by 1,6 m generated by LiDAR was used. When performing the laser scan bridges and under crossings from streams will often appear as barriers in the terrain model and will generate a false positive for a potential ponding area. It is therefore of upmost importance knowing how to evaluate the outcome when calculating potentially flooded areas, as the ponding areas are used directly as input to the flood model. An example is shown in figure 4, which illustrate the difference in potential flooded areas before and after removing bridges and underpasses. This analysis can also be used to identify risk areas in relation to streams, since it illustrates where the capacity of stream underpasses can be critical for upstream flooding.

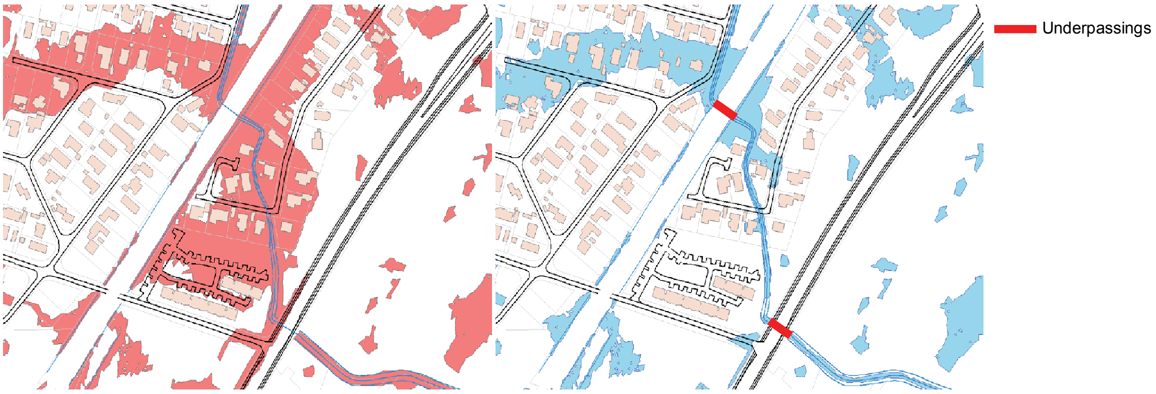

Figure 4. Calculated ponding areas using a raw terrain model (left) and modified terrain model (rigth).

3.1 Validation

The model setup was validated against a 1D-2D flood simulation done in Odense, Denmark (Nielsen et al, 2008). In this setup the 2D description of overland flow was validated against a high resolution photo documentation of one flooding event. The result is illustrated in figure 5 illustrating the comparison between the calculated potential flood areas, the 1D-1D model and the 1D-2D model. The results for the 1D-1D simulation and 1D-2D simulation corresponds very well and differences in calculated flood depths are below 5 cm at the ponds. The 2D model gives a finer nesting of the flood depths below 5 cm and distribution of flowing water on the road due to vector calculated surface flow.

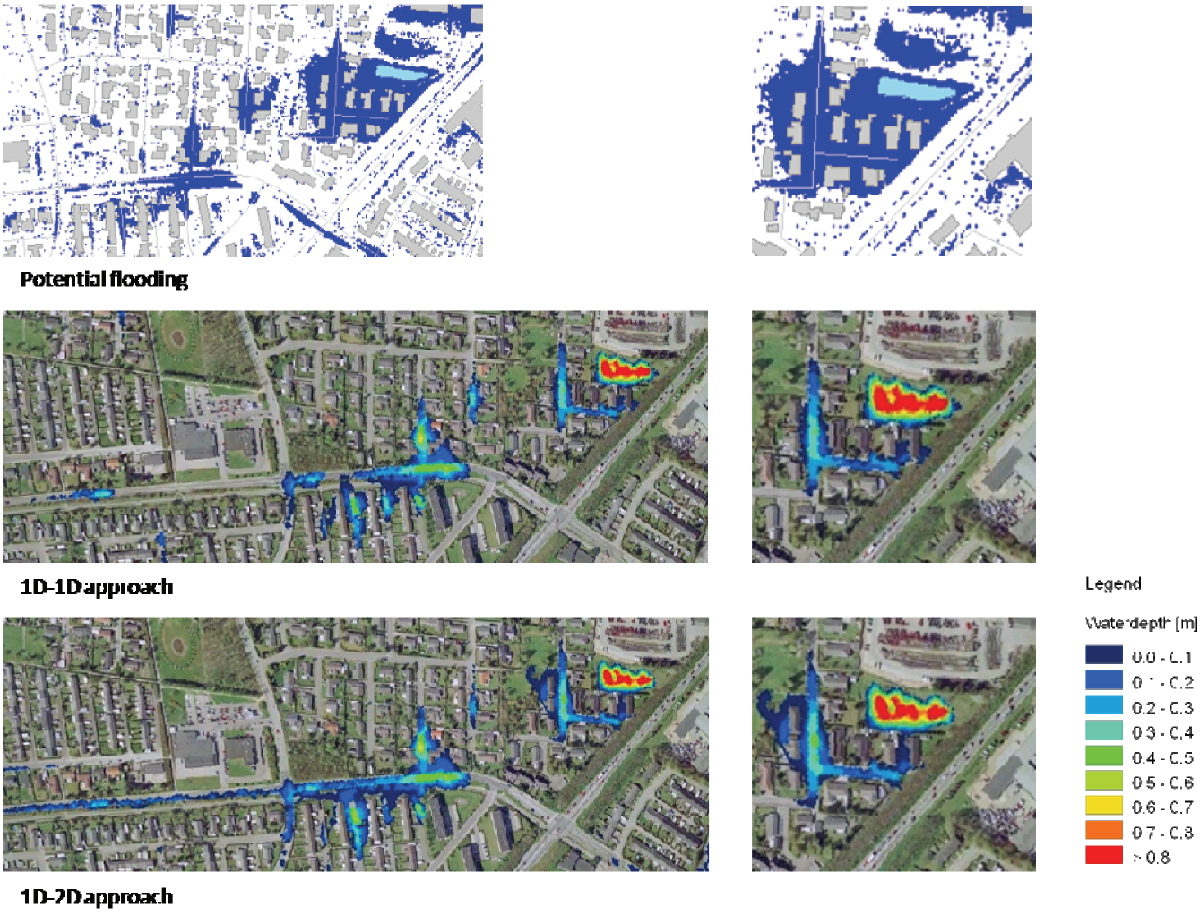

Figure 5. Results showing potential flooded areas (top), 1D-1D simulation (middle) and 1D-2D simulation of the same event (bottom).

3.2 Sensitivity analysis

Important variable parameter for the 1D-1D model is the threshold value for the depth in each depression. Decreasing the threshold depth will increase the level of details but it will also increase computation time and the required memory allocation. Since the main purpose by using the 1D-1D method is large scale calculations and screening it is important to select a threshold depth satisfying the purpose. And it is important to choose a hydrodynamic model system and model-setup capable of calculations with large timesteps.

The model setup was tested for different threshold depths. Testing was done on the threshold depths of 20, 30, 40 and 50 cm. Sensitivity analysis was carried out on the threshold depths and volume. It was found that the calculated flood depths had an average difference of less than 5 cm per 10 cm change in threshold depth and less than 10% change in calculated flood volume per 10 cm change in threshold depth. In figure 6 it is illustrated how some potential flooded areas will be left out of the map depending on the input threshold depth. Calculated flood depths using 20 cm as minimum input depths for the same area is shown as well. The most critical flooded areas are located in ponds with a minimum depth of more than 30 cm.

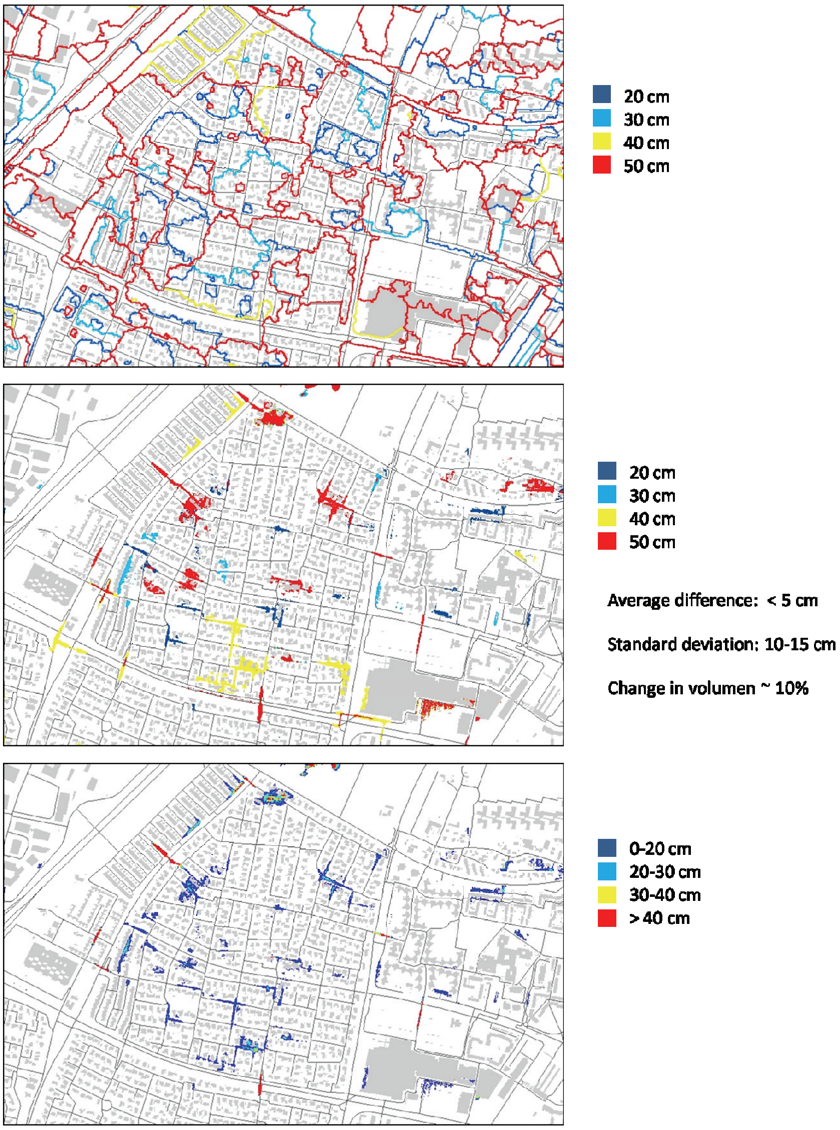

Figure 6. Catchment areas corresponding to different minimum levels for ponds as input (top) and calculated ponding areas corresponding to different threshold depths as input (middle). Below is shown calculated flood depths using a 20 cm threshold depth for pond calculation

When screening for flood risk areas in a very large catchment it is important that the developed method is capable of remaining numerical stable for larger timestep. Sensitivity analysis on the mass balance in relation to water generated in network was carried out for timesteps (dT) of 2, 5 and 10 sec. It was found that time step up to 10 sec would be acceptable for this study.

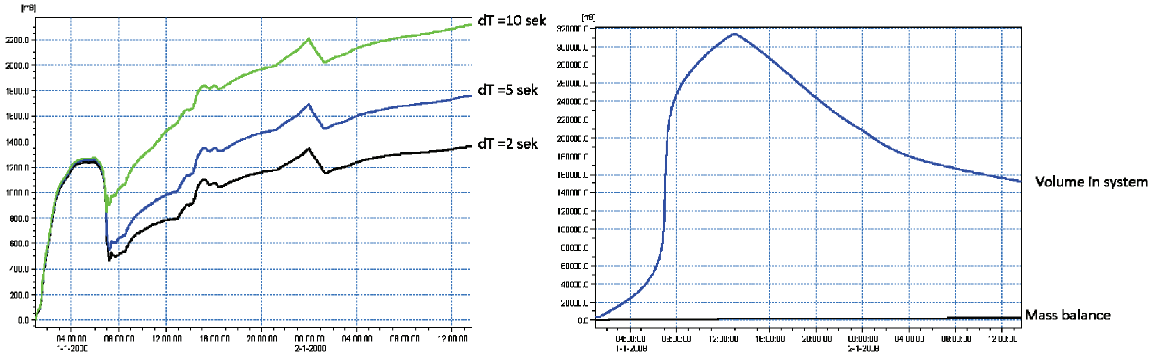

Figure 7. Left: Effect of different time step on water generated in the network. Right: Water generated in the network compared to the total water volume in the system

Detailed sensitivity studies on inaccuracies using this simple weir routing method instead of 2-D vector based methods is not applied yet. Differences between 2D, 1D and analytical solutions have to be investigated for slope and distances between ponds etc.

3.3 Comparisons of procedure levels

The GIS based algorithm integrating procedure can be divided into three levels, where level 1 is the overland ponds found from the digital surface model, level 2 is overland basins evaluated with a rain event (1D surface model) and level 3 is the full 1D-1D model. Level one is independent of the rain event.

Figure 8, where the three levels are compared, illustrate the typical picture where DTM ponds have large spatial flood areas compared with level 2 and 3. The 1D surface model has larger flooded areas upstream and minor areas downstream the collection system compared with the 1D-1D model, since the collection system transport water to the downstream parts. The conclusion on comparing the 1D surface model and the 1D-1D model is that ignoring the collection system, results in underestimated flooding downstream and overestimated flooding upstream the collection system. The inaccuracy between the two model levels are however of minor significance compared to calculating the potential flood only.

Depending on data available different simulation levels can be chosen. E.g. missing pipe information a 1D surface approach can be used.

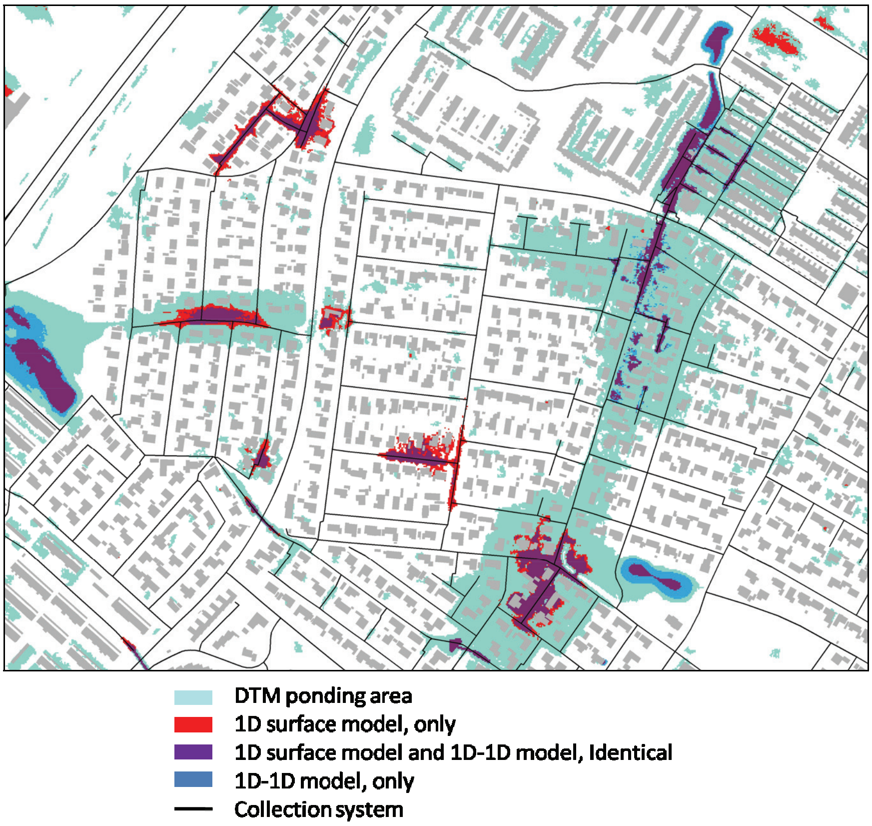

Figure 8. Comparison of ponding areas, 1D surface model and 1D-1D model.

4 CASE STUDY

The method was applied on a large separate system with a catchment area of 10.900 ha in Greve, Denmark. The area has been subject to severe flooding in 1984, 1987, 2002 and 2007. The model setup consisted of around 7.300 links, 7.300 nodes, 2.500 surface ponds and 13.600 flow paths and weirs. For each manhole a catchment area was calculated and rainwater was routed to the system by use of a time-area function. This was found to be an acceptable method since the volume of the water from precipitation was one of the most important factors when calculating flooding (Nielsen et al, 2008). The model was run with a threshold depth of 20 cm and a time step of 10 seconds. The grid size used was 1.6 m by 1.6 m. This enabled generating a flood map for entire municipality in one model setup.

For different return periods maximum water levels were calculated for each ponding area and visualized in a GIS environment, see figure 9. The model setup has been used by the utility for prioritizing the work needed to prepare the sewer system for the anticipated increase in rain and setup emergency plans. These plans have already been set in motion and prevented a flooding event in June 2009. (e.g. Paludan et al, 2010 forthcoming).

Further work is being done on the model complex and streams are being implemented in the framework. Sensitivity analysis on soil infiltration and stream capacity is being carried out at the moment.

Figure 9. Example of a simulation of flooded areas for a specific return period displayed in the GIS environment.

The model setup was also applied to a densely populated combined sewage system in Odense, Denmark, with a catchment area of more than 5.000 ha. The model consisted of more than 21.000 manholes, surface basins and weirs. The open basins and streams are automatically handled by the GIS algorithm to prevent double volume in the model setup. It was found that a threshold value of 40 cm was sufficient for creating a flood risk map for the whole system in one model setup.

The framework focuses on flooding events due to excess overland flow occurring for rainfall exceeding the design criteria of the sewage system. It is not possible to visualize flow on the surface during a flooding event. However pathways can be implemented in the sewage model as open channels for areas identified as hotspots if more detailed information is needed.

For the above described large-scale case study a damage control strategy for a village area in Greve were developed on basis of the 1D-1D model. The village is located in a countryside area having a small stream running through the developed area. Combinations of upstream urban overflow and a grassland drainage system generate a risk for overland flooding in the village and following material damage. Downstream the village the stream conveys into a larger urban area with high damage risk when flooded.

The solution was a two step low-tech damage control plan for events larger than the system capacity. Two grassland areas suitable for storing water was found along the stream upstream the village and a large natural field basin was detected south of the village. The control strategy for extreme flooding events can be established by an online level measurement in the village rainwater basin, two manually operated gates and storage of sandbags. At level one the upstream manual gates are suppressing water in basins along the stream. At level two when the upstream basins area filled, strategic placement of the sandbags will direct overland flooding water to the southern field basins. The emergency plan is illustrated in figure 10.

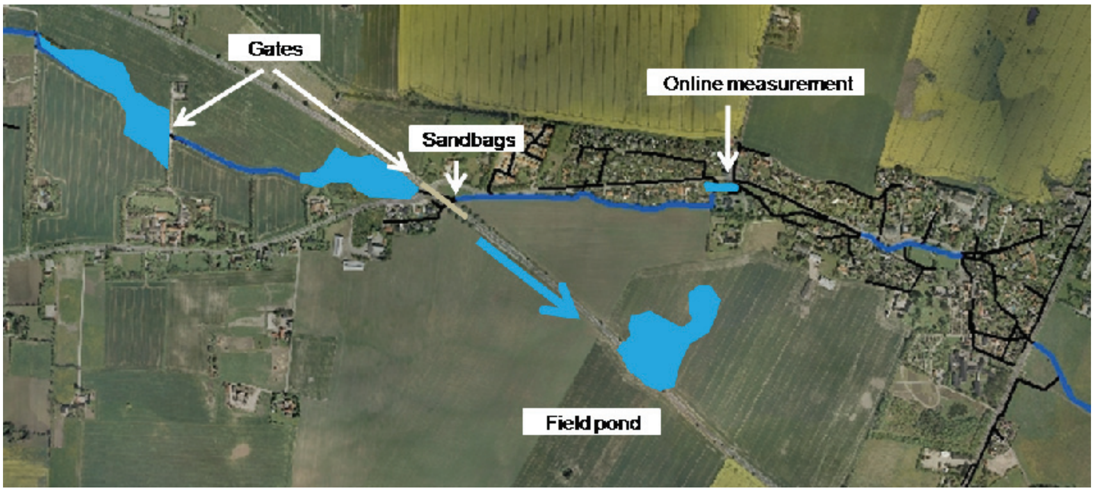

Figure 10. Damage control strategy based on knowledge from 1D-1D modelling.

5 CONCLUSIONS

A fully automated method for creating flood risk maps for large catchments was developed. The concept is based on a GIS algorithm combining known techniques for modelling of sewer flow with novel techniques describing overland flow. This is an important step in ensuring a fully integrated modelling of urban flood on a very large catchment scale. The method outlined represents an efficient system for planning and management of urban drainage systems suffering from urban flooding and can help utilities prepare for the challenge of climate change. Critical flood areas can be outlined and the model setup can help to identify where more detailed modelling is needed.

Sensitivity analysis was carried out on the threshold depths and volume. It was found that the calculated flood depths had an average difference of less than 5 cm using either 20 cm or 50 cm depths as threshold inputs and less than 10% change in calculated flood volume.

Depending on data available different simulation levels can be chosen. E.g. missing pipe information a 1D surface approach can be used.

The full 1D-1D method was used on a catchment of 5.000 ha and 10.900 ha. Manual work was not needed in the progress and the outcome was valuable flood risk maps (e.g. T=10, 25, 50 and 100 years), which can be used as a first step in flood management or as a direct source for developing damage control strategies and emergency plans.

Due to the short computational time this framework can also be used for real time control or warning in case of a flooding event.

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