Comparing modelling techniques for analysing urban pluvial flooding

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Abstract

Short peak rainfall intensities cause sewer systems to overflow leading to flooding of streets and houses. Due to climate change and densification of urban areas, this is expected to occur more often in the future. Hence, next to their minor (i.e. sewer) system, municipalities have to analyse their major (i.e. surface) system in order to anticipate urban flooding during extreme rainfall. Urban flood modelling techniques are powerful tools in both public and internal communications and transparently support design processes. To provide more insight into the (im)possibilities of different urban flood modelling techniques, simulation results have been compared for an extreme rainfall event. The results show that, although modelling software is tending to evolve towards coupled 1D-2D simulation models, GIS techniques, using an accurate Digital Elevation Model, prove to be an easy and fast alternative to identify vulnerable locations in hilly and flat areas. In areas at the transition between hilly and flat however, coupled 1D-2D simulation models give better results since catchments of major and minor system can differ strongly in these areas. During the decision making process, GIS techniques can provide a first insight that can be complemented with complex simulation models for critical locations.

Keywords

Extreme rainfall, Geographic Information Systems, modelling techniques, simulation models, pluvial flooding, urban flood modelling

INTRODUCTION

In recent years, the overload frequency of urban drainage systems due to extreme rainfall has increased, leading to damage by blocked main roads and flooded properties. This is caused by a combination of three factors (Kluck, 2011):

- Increasing extreme rainfall intensities due to climate change;
- Additional pavement and buildings;
- Decreasing space for water storage on streets and reducing surface level differences between buildings and street.

Dutch legislation requires that municipalities collect and process surplus runoff in an efficient manner. Hence, more efficient utilization of public space, also called the major system (Djordjevic et al., 1999; Figure 1), is necessary. To date however, most municipalities focus on the subsurface drainage system, also called the minor system. In The Netherlands, the minor system has usually been developed to prevent pluvial flooding during a rainfall event with an intensity of 20 mm/h.

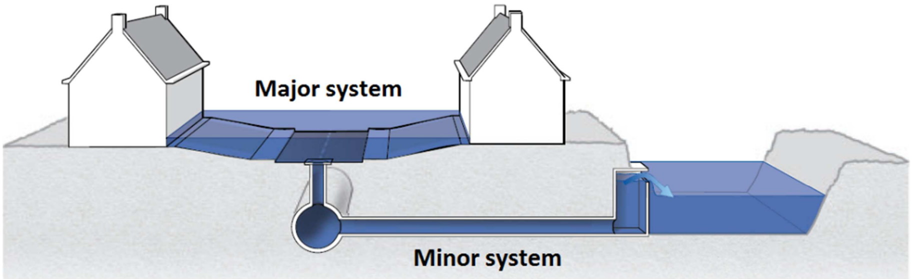


Figure 1. Interaction of major and minor system (RIONED Foundation, 2007).

Since extreme rainfall by definition does not occur frequently, many municipalities do not have any insight into the vulnerability of their public space to pluvial flooding (Geldof and Kluck, 2008). Furthermore, they have not considered a desired level of protection (Ten Veldhuis, 2010). However, when damage due to extreme rainfall occurs, prevention of the damage recurring becomes urgent, possibly leading to very expensive measures instead of a solid plan that is realized over many years. To anticipate on future events, municipalities should evaluate storm water discharge through the minor system and storage and flow in the major system. For this insight, modelling techniques are necessary.

Urban flood modelling techniques are powerful tools in both public and internal communication and they transparently support design processes. For the design of sewer systems, computer models are used in which flow through the minor system is simulated. However, these models are not suited for the calculation of flow through the major system (Russo et al., 2011). When water levels rise above surface level, this is schematized in the models as a water column above the manhole. This is not a realistic assumption in situations where the minor system is heavily overloaded and water flows over the surface.

In recent years, different modelling techniques have been developed for simulating flow through the major system. The choice for one of these techniques effects simulation results and decision making about anticipating extreme rainfall. Although modelling software is tending to evolve towards complex simulation models, choosing the most appropriate modelling technique means balancing accuracy, computation time, data needs and communication possibilities. Hence, it is not straightforward what modelling technique should be used in what situation.

MODELLING TECHNIQUES

Urban runoff during short peak rainfall can be simulated with coupled 1D-2D simulation models, simulating one-dimensional flow through the minor system and two-dimensional flow through the major system. However, it is also possible to simulate two-dimensional flow through the major system without simulating the minor system, using Geographic Information Systems (GIS).

GIS techniques

GIS techniques use a high-resolution Digital Elevation Model (DEM) and provide insight in flow paths and depressions for a certain rainfall amount. The discharge through the minor system can be accounted for by assuming a certain amount of precipitation to be discharged by the sewer system. GIS techniques only provide insight in overland discharge and make a quick scan of pluvial flooding with limited effort in a few minutes time for medium sized urban areas.

Figure 2 shows an example of a GIS analysis. Based on a DEM (left part), the GIS technique determines flow paths and water depths (right part).

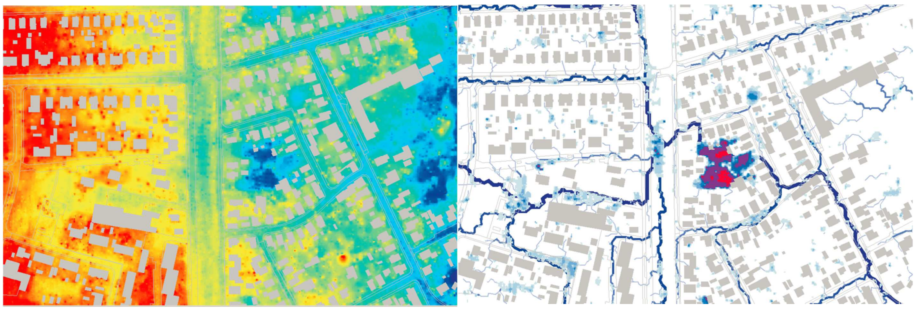


Figure 2. Left: Digital Elevation Model (red means high-lying, blue means low-lying). Right: water depths (purple means deep, light blue means shallow) and flow paths (Kluck, 2011).

Important points of attention for using GIS techniques are:

- They do not take interaction between major and minor system into account;
- Most GIS techniques use the so-called "rolling ball" algorithm that tracks flow paths by determining for each grid cell which of the adjacent grid cells is the lowest. Hence, the algorithm always determines only one preferred flow path;
- Since they only determine flow paths and water depth, it is not possible to determine flooding duration.

Coupled 1D-2D simulation models

Coupled 1D-2D simulation models of the minor (1D) and major (2D) system currently provide the most realistic representation of the water flow at extreme events. These models schematize the major system as a grid or Triangular Irregular Network, where cells exchange water with neighbouring cells and with the 1D model of the minor system by manholes or gullies. Simulation times depend on the number of elements in the 2D domain and are usually in the range of hours to days for medium sized urban areas.

Although coupled 1D-2D simulation models have improved simulation of flood propagation in urban watersheds, the complexity of physical processes that must be simulated and the limited amount of data available for calibration may lead to high uncertainty in the model results (Maksimovic et al., 2009; Leandro et al., 2009). Important points of attention for using coupled 1D-2D simulation models are:

- At the moment, the downside of these models is a large computational effort that make them unsuitable for operational management and quick predictions;
- Most coupled models neglect loss of pressure height due to interaction of major and minor system, although it is necessary to realistically represent the interaction between the sewer system and the urban surface (Ochoa Rodriguez et al., 2012). Even when the schematization is improved by simulating losses, uncertainty remains due to blockages and the influence of flow velocity over gullies;
- Most simulation models couple the discharging area to sewerage pipes and manholes and do not take pluvial flooding due to limited flow capacity of gullies and streets into account.

General shortcomings and uncertainties

Next to shortcomings and uncertainties linked to modelling techniques, some sources of uncertainty are independent of the chosen modelling technique. This means that simulation results should be seen as a guess of what might happen at an extreme event, or at least with a lot of reserve. The main general shortcomings and uncertainties of urban flood modelling techniques are:

- For a good description of the major system, a spatial resolution of 0,50 m to 1,00 m is required (Mark et al, 2004; Bertram et al, 2009). Lower resolution data can cause wrong predictions of surface flow;
- Discharge of unpaved areas is difficult to predict and depends on soil conditions, slope, vegetation and precipitation characteristics;
- In general, urban water management models have not been validated for extreme rainfall events;
- When a DEM is obtained by airplane scanning, surface features as tunnels, walls and underpasses are not taken into account. Although modern measurement techniques, e.g. LIDAR and Mobile Laser Mapping, improve data obtaining, it still costs a lot of effort to map all these features correctly. Furthermore, the urban area is changing continuously.

CASE STUDY

To compare different urban flood modelling techniques, a case study was carried out for an extreme rainfall event in the Dutch coastal municipality of Noordwijk. Results of a GIS-analysis (WOLK, Tauw Consultants) were compared with a 1D-2D simulation model (SOBEK, Deltares) under the following conditions:

- Uniform distributed precipitation of 60 mm in one hour, which is the estimated hourly rainfall amount with a statistical frequency of once every hundred years, assuming two degrees increase in temperature due to climate change (Van der Meulen et al, in preparation);
- A DEM with a spatial resolution of 1x1 m.

Since it was expected that conclusions can differ between different types of areas, three areas have been investigated in more detail (Figure 3):

- A (old centre between dunes): a bowl-shaped area with height differences up to about twenty metres with a combined sewer system;
- B (transition between dunes and flat area): an area with height differences up to about seven metres and a large surcharge of storm water from the old centre by the sewer system;
- C (flat living area): an area with height differences of less than a metre.

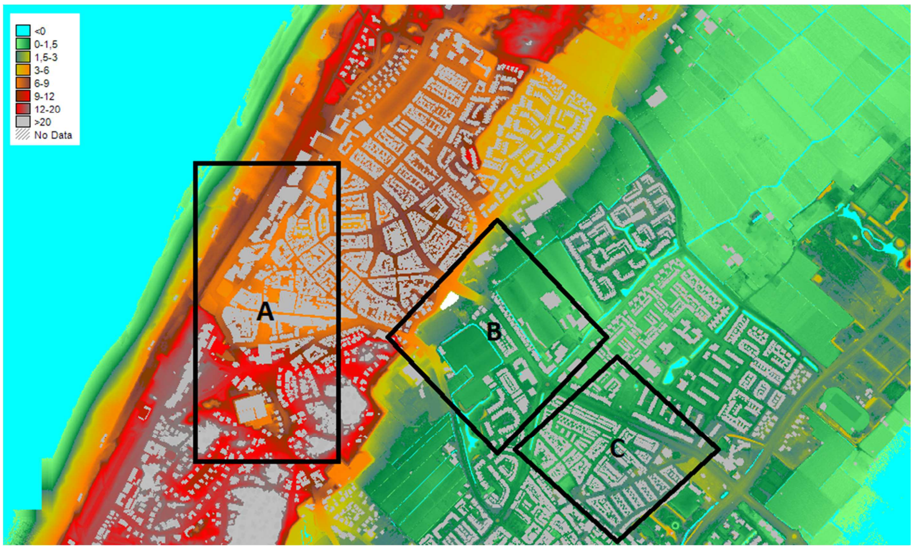


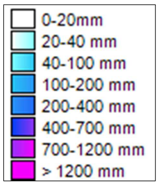
Figure 3. Digital Elevation Map of the municipality of Noordwijk (m + sea level) and locations investigated in more detail.

During recent years, the municipality of Noordwijk has often faced urban pluvial flooding at several locations, causing traffic problems and water in buildings. On 26 August 2010, heavy rainfall with an intensity of 41,8 mm in three hours (maxima: 25 mm/h and 4 mm in five minutes) caused large damage. Prior to the maximum rainfall, small precipitation amounts reduced the storage capacity of the minor system, especially in the lower part of the system. Although the amount of rainfall is not very extreme, it exceeds the design rainfall for the minor system (20 mm/h). The mentioned problems show that the major system could not handle the excess amount of rainfall.

RESULTS

A (old centre between dunes)

All modelling techniques predict water on street at locations that are well-known from complaints by inhabitants (**Figure 4** and Figure 5). However, some vulnerable locations, as predicted by the models, are not registered in the municipality database. This can be caused by modelling deviations as mentioned before, by the fact that the simulated rainfall intensity differs from actual intensities that have caused flooding or by the fact that not all flood locations have been recorded.



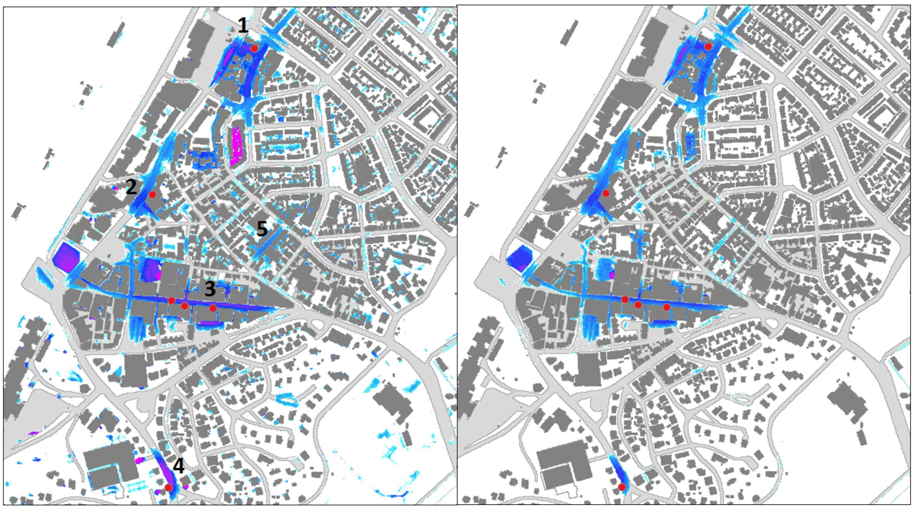


Figure 4. Depth of water on street in area A, determined by a GIS technique (left) and a coupled 1D-2D simulation model (right). The red dots mark known vulnerable locations.

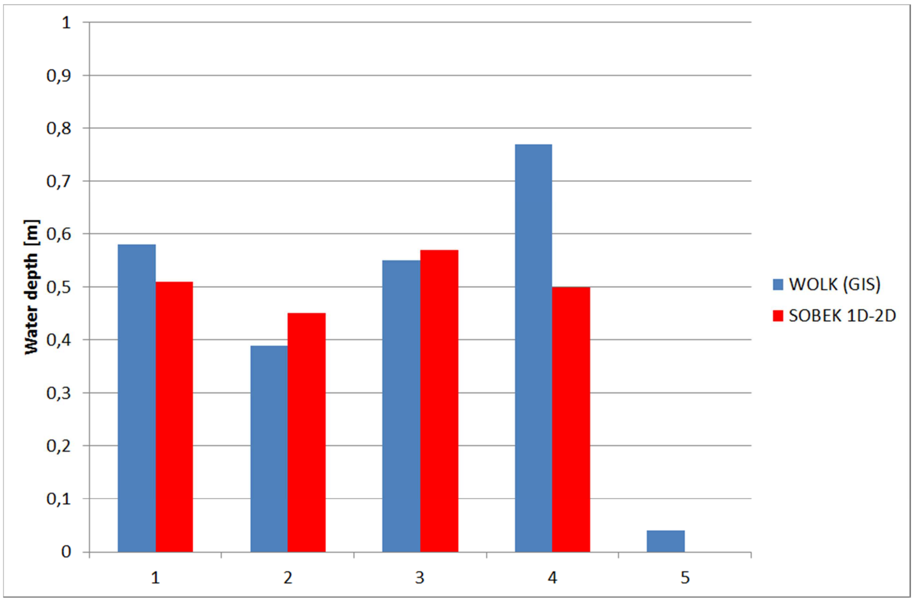


Figure 5. Maximum water depths for each modelling technique at known vulnerable locations in area A. The numbers correspond with the locations in

Figure 4.

Both modelling techniques show in general flooding at the same locations, although there are some differences for specific locations. E.g., the GIS technique predicts flooding of location 5, whereas the coupled 1D-2D simulation model predicts no flooding for that location. Since during the 2010 rainfall event, no flooding occurred here and hence, the discharge capacity of the minor system is larger than the assumed 20 mm/h at this location, incorporating the minor system to the model is important for this location.

Furthermore, it is notable that the GIS technique computes a water depth of more than 1,20 m at the pink location in the left part of

Figure 4, although this area is not recognized as vulnerable location. The GIS technique simulates a flow path towards this area through an alley that can discharge only a small amount of water. By taking hydraulic constrains of the alley into account (i.e. by using a simulation model), one gets a better prediction of the surcharge volume, which is insufficient to fill the area completely.

B (transition between dunes and flat area)

For areas at the transition between hilly and flat, it is crucial to take the minor system into account. The coupled 1D-2D simulation model simulates considerably more flooding in area B than the GIS technique does (

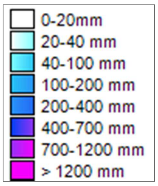


Figure 6) and its results match experiences in praxis better. This area has a large subsurface surcharge from the city centre towards the flat area and catchments of major and minor system differ strongly. Hence, the assumption that the sewer system has a capacity of 20 mm/h for the area itself is not a valid one.

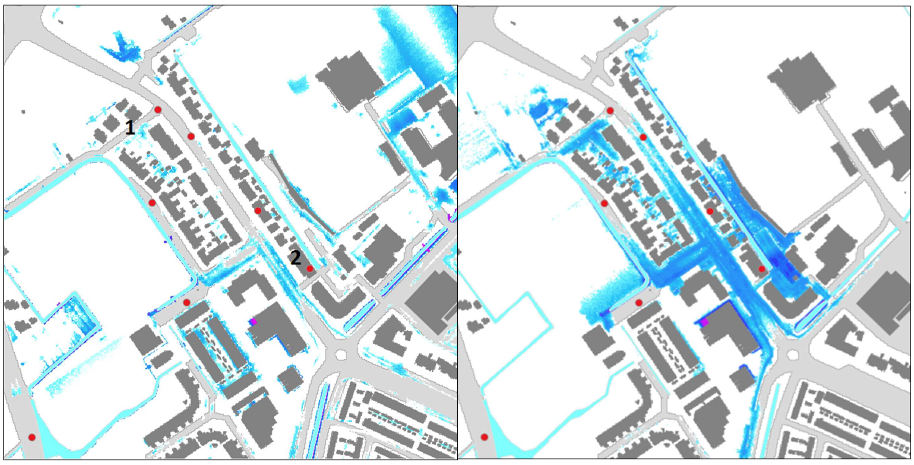


Figure 6. Depth of water on street in area B, determined by a GIS technique (left) and a coupled 1D-2D simulation model (right). The red dots mark known vulnerable locations.

For two known vulnerable locations in this area, the coupled 1D-2D simulation model simulates considerably larger water depths than the GIS technique (Figure 7). Although it is known that flooding in this area already occurs at rainfall intensities of 25 mm/h, the GIS technique hardly predicts any flooding for a rainfall intensity of 60 mm/h. Hence, it is concluded that this technique can underestimate flooding depth and extent in areas at the transition between hilly and flat areas and that coupled 1D-2D simulation models are more suitable for this type of areas since they consider sewer flow.

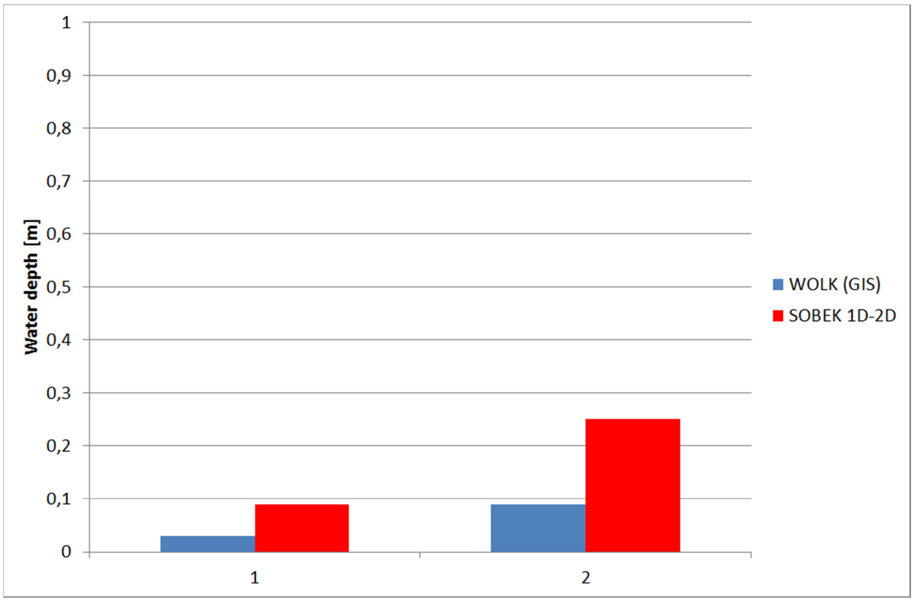


Figure 7. Maximum water depths for each modelling technique at known vulnerable locations in area B. The numbers correspond with the locations in

Figure 6.

C (flat living area)

For the flat living area, hardly any differences are visible between the results of the GIS analysis and the coupled 1D-2D simulation model (Figure 8). Both modeling techniques predict a large flooding extent, although only few complaints have been registered. Again, this is not necessarily a model deviation, since during the last years, the simulated hourly rainfall amount has not been recorded. For the intensity that has been experienced, no problems occur, although beyond a certain critical intensity, flood extend can rapidly increase (Gersonius et al., 2011).

Figure 8. Depth of water on street in area C, determined by a GIS technique (left) and a coupled 1D-2D simulation model (right). The red dots mark known vulnerable locations.

For the flat living area, the GIS technique predicts nearly the same water depth as the coupled 1D-2D simulation model (Figure 9). The surcharge and discharge by the minor system is not as important to flooding as it is for areas at the transition between hilly and flat areas.

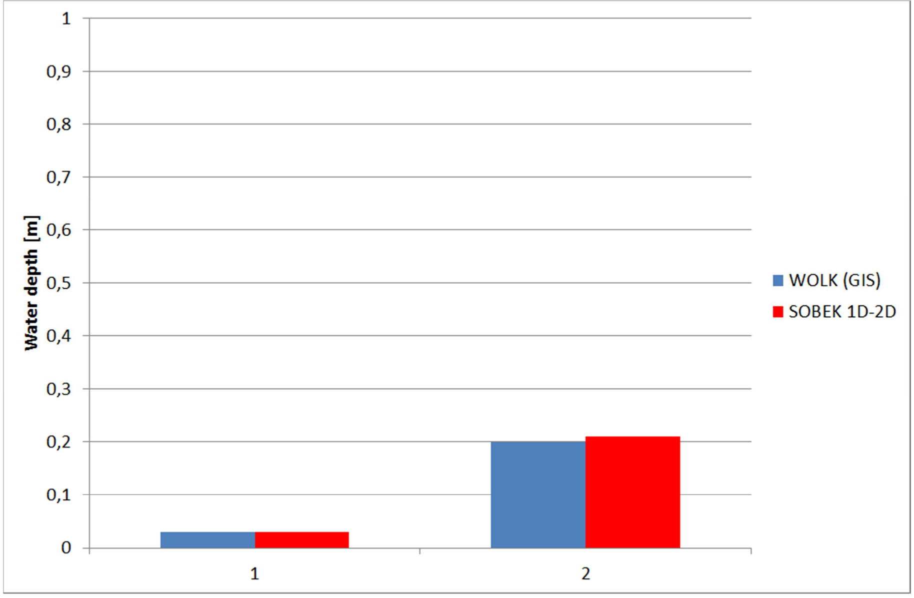


Figure 9. Maximum water depths for each modelling technique at known vulnerable locations in area C. The numbers correspond with the locations in Figure 8.

DISCUSSION

Modelling software is tending to evolve from traditional computer models for flow through the minor system towards coupled 1D-2D simulation models. Based on the results of this survey, this transition is justified. Coupled 1D-2D simulation models take more physical processes into account than GIS techniques and hence, are expected to provide the most accurate results. However, one is also faced with a large uncertainty when using coupled models, introduced by the assumptions that major and minor system only interact at manholes and that overland runoff only occurs because of surcharging of the minor system. Regardless which modelling technique is chosen, most uncertainty is introduced by general sources of uncertainty such as the spatial resolution of the DEM, that has to be smaller than the typical size of landscape elements, the surface discharge of unpaved areas, that depends on soil type, slope, presence of vegetation and rainfall intensity, recent changes in the actual situation and blocking of gullies. Furthermore, the lack of data for model validation leads to high uncertainty in the model results.

Choosing the most appropriate modelling technique means balancing accuracy, computation time, data needs and communication possibilities. The case study shows that GIS techniques identify most vulnerable locations and hence, their accuracy is sufficient to carry out quick scans for urban pluvial flooding in most situations. Furthermore, their computation time and data needs are far less than those of coupled 1D-2D simulation models and they provide extensive communication possibilities. During the decision making process, GIS techniques provide a first insight and are an easy and fast alternative to assess flood risks and to analyse the effect of possible mitigation measures. For critical locations, an extra analysis of the interaction between major and minor system can be carried out by using a coupled 1D-2D simulation model. These critical locations can be potential damage locations, locations where expensive measures are foreseen or areas at the transition between hilly and flat areas.

REFERENCES

Bertram, D., Minto, J., Haynes, H., and Roberts, M. (2009). Developing surface water management models: Integrating urban drainage features. In: *33rd IAHR Congress: Water Engineering for a Sustainable Environment, Vancouver, Canada*.

Djordjevic, S., Prodanovic, D., and Maksimovic, C. (1999). An approach to simulation of dual drainage. *Water Science and Technology*, **39**(9), 95-103.

Geldof, G.D., and Kluck, J. (2008). The three points approach. In: *Proceedings of 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK*.

Gersonius B., Ashley R., Jeuken A., Pathirana A. & Zevenbergen C. (2011). Accounting for climate change in urban drainage and flooding: Contrasting alternative approaches to devising adaptive strategies. In: *12th International Conference on Urban Drainage, Porto Alegre, Brazil*.

Kluck, J. (2011). Water in en om de stad. Meer energie voor water. *Inauguration, Amsterdam University of Applied Sciences, School of Technology, Lectureship Urban Water Management*.

Leandro, J., Chen, A., Djordjevic, S., and Savic, D. (2009). A Comparison of 1D/1D and 1D/2D Coupled (Sewer/Surface) Hydraulic Models for Urban Flood Simulation. *Journal of Hydraulic Engineering*, **135**(6), 495-504.

Maksimovic, C., Prodanovic, D., Boonya-aroonnet, S., Leitao, J., Djordjevic, S., and Allitt, R. (2009). Overland flow and pathway analysis for modeling of urban pluvial flooding. *Journal of Hydraulic Research*, **47**(4), 512-523.

Mark, O., Weesakul, S., Apirumanekul, C., Boonya-aroonnet, S., and Djordjevic, S. (2004). Potential and limitations of 1D modeling of urban flooding. *Journal of Hydrology*, **299**(3-4), 284-299.

Ochoa Rodriguez, S., Ten Veldhuis, J.A.E., Maksimovic, C., Schertzer, D., and Willems, P. (2012). Scientific challenges for enhancing urban pluvial flood resilience. *Geophysical Research Abstracts*, **14**, EGU2012-14324.

RIONED Foundation (2007). Klimaatverandering, hevige buien en riolering. Visie van Stichting RIONED.

Russo B., Pouget L., Sunyer D., Malgrat P. & Theias H. (2011). Flood risk assessment through a 2D-1D coupled modeling approach including impact of climate change in Barcelona. In: *12th International Conference on Urban Drainage, Porto Alegre, Brazil*.

Ten Veldhuis, J.A.E. (2010). Quantitative Risk Analysis of Urban Flooding in Lowland Areas. *PhD thesis, Delft University of Technology, Delft*.

Van der Meulen, J., Kluck, J., Van Dijk, E., Straatman, J.H.M. (in preparation). Extreme neerslag. Dat is toch niet normaal.