

Comparing modelling techniques for analysing urban pluvial flooding

E. van Dijk, J. van der Meulen, J. Kluck and J. H. M. Straatman

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 one-dimensional (1D)–two-dimensional (2D) simulation models, surface flow models, 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 systems can differ strongly in these areas. During the decision making process, surface flow models can provide a first insight that can be complemented with complex simulation models for critical locations.

Key words | extreme rainfall, modelling techniques, pluvial flooding, simulation models, urban flood modelling

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INTRODUCTION

In recent years, the overload frequency of urban drainage systems due to extreme rainfall has increased, caused by a combination of increasing extreme rainfall due to climate change, additional pavement and decreasing space for water storage on streets. 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, and do not have insight into the vulnerability of their public space to pluvial flooding (Geldof & Kluck 2008) or a desired protection level (Ten Veldhuis 2010). When damage occurs, prevention of recurring becomes urgent, leading to expensive measures instead of a solid plan that is realized over many years. To anticipate 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 that simulate flow through the minor system. However, these models are not suited for simulation of the major system, since when water levels rise above surface level, they suggest a water column above the manhole instead of flow over the surface (Maksimovic & Prodanovic 2001; Mark *et al.* 2004; Russo *et al.* 2011). 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. Choosing one of these models 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. An important point in the choice of the models is the fact that these

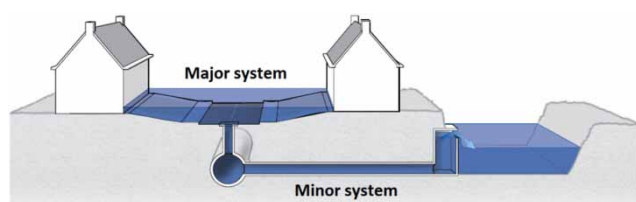


Figure 1 | Interaction of major and minor system (RIONED Foundation 2007).

models can hardly be calibrated for extreme rainfall situations, due to the fact that these events are very rare and descriptions of occurred floods are in general not accurate enough. Hence, it is not straightforward what modelling technique should be used in what situation. Although there are a number of studies that compared different modelling techniques in river modelling, these are scarce in urban flood modelling and focussed on one-dimensional (1D) vs two-dimensional (2D) surface flow models (Lhomme *et al.* 2005) or 1D–1D vs 1D–2D simulation models (Leandro *et al.* 2009).

Therefore, this study presents a comparison of a surface flow model and a simulation model, both of which can be used to generate flood hazard and flood risk maps for urban flood modelling based on the same surface data input. It is investigated to what extent uncertainty due to the choice for a certain modelling technique has effect on derived flood hazard maps. Based on the results, urban water experts should be better capable of choosing the best modelling strategy for analysing possible flood hazard and flood risk.

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 surface flow models.

Surface flow models

Surface flow models provide fast insight in flow paths and depressions based on a digital elevation model (DEM, Figure 2).

A major drawback of surface flow models is that they do not take interaction between the major and minor system into account. Furthermore, most surface flow models use the so-called ‘rolling ball’ algorithm that only determines one preferred flow path and do not determine flooding duration.

Coupled 1D–2D simulation models

Coupled simulation models of the minor (1D) and major (2D) system schematize the major system as a grid or triangular irregular network, where cells exchange water with neighbouring cells and the 1D model. Simulation times are considerably longer than those of surface flow models and the complexity of physical processes and the limited amount of calibration data lead to high uncertainty in the model results (Maksimovic *et al.* 2009; Leandro *et al.* 2009).

A major drawback of coupled 1D–2D simulation models is that, at the moment, large computational efforts make them unsuitable for quick predictions. Furthermore, most coupled models neglect loss of pressure height at gullies, although this is necessary to realistically represent the interaction between the major and minor system (Ochoa Rodriguez *et al.* 2012). Even when these losses are schematized, uncertainty remains due to blockages and the influence of flow velocity over gullies.

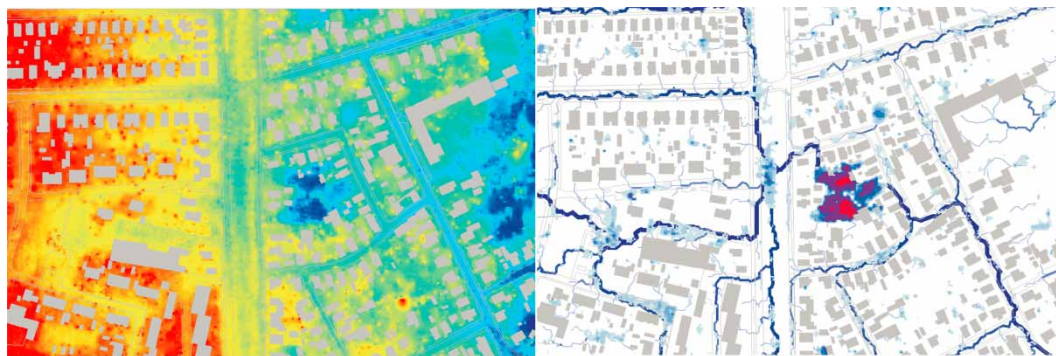


Figure 2 | Left: digital elevation model. Right: water depths (dark means water on the streets) and flow paths (in the full cover version of this figure (available online at <http://www.iwaponline.com/wst/toc.htm>), the red and blue (left figure) refer to high lying and low lying respectively; purple and blue (right figure) refer to deep and shallow, respectively).

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 with a lot of reserve (Mark *et al.* 2004; Bertram *et al.* 2009). For example, the major system is described as a grid or a triangular network so that small significant irregularities in the street pattern are not taken into account. Furthermore, it is difficult to predict discharge of unpaved areas, especially for extreme events. Finally, most urban storm water management models have not been validated for extreme rainfall events.

CASE STUDY

During recent years, the Dutch coastal municipality of Noordwijk (Figure 3 and Table 1) has faced urban pluvial flooding several times, causing traffic problems and water in buildings. On 26 August 2010, heavy rainfall with an intensity of 41.8 mm in 3 hours (maxima: 25 mm/h and 4 mm in 5 minutes) caused large damage. Prior to the maximum rainfall, small precipitation amounts reduced the storage capacity of the minor system. Although the amount of rainfall was not very extreme, it exceeded 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.

To compare different urban flood modelling techniques, a case study was carried out for an extreme rainfall event in Noordwijk. Results of a surface flow model (WOLK, Tauw Consultants, using a 'rolling ball' algorithm) were compared with a 1D–2D simulation model (SOBEK, Deltares, using Saint Venant equations) for uniform distributed precipitation of 60 mm in 1 hour, which is the estimated hourly rainfall amount with a statistical frequency of once every 500 to 1,000 years (Overeem *et al.* 2008). Since it was expected that results do not differ much between different software packages using the same modelling technique, the comparison was limited to these two packages. For the surface flow model, the precipitation was corrected for the design capacity of the minor system (20 mm/h). The 1D–2D simulation model used data about the minor system from the municipal sewer database. To describe the surface, an actual DEM with a spatial resolution of 1×1 m was used with a maximum vertical uncertainty of 5 cm. Unfortunately, no measurements, aerial photographs or satellite data of pluvial flooding events in the past are available and, hence, model validation could only be carried out by comparing results with the municipality complaints database. This is not ideal, since the estimated rainfall for the situation of the complaints was about 42 mm in 3 h and the modelling has been set up for 60 mm/h. However, it is the best available information.

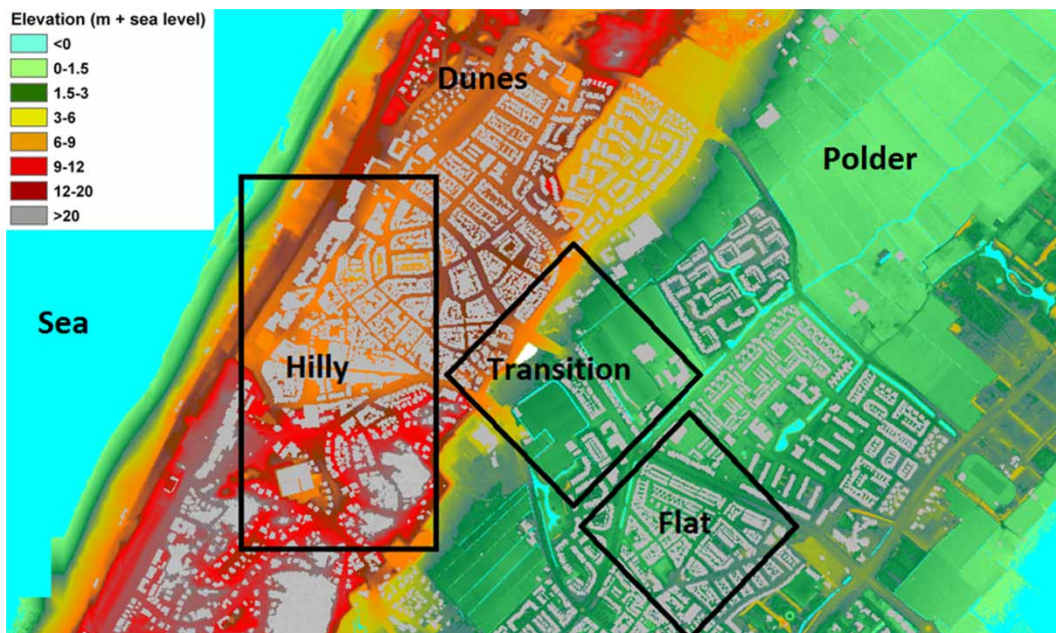


Figure 3 | Digital elevation map of the municipality of Noordwijk and location of study areas.

Table 1 | General characteristics of the urban drainage system of Noordwijk

Paved area (ha)	170
Unpaved area (ha)	73
Number of inhabitants	34,009
Type of sewer system	Combined
Pump capacity (m ³ /hr)	1,730
Storage below lowest spillway (mm)	4.6
Number of spillways	5

Since it was expected that conclusions can differ between different types of areas, three areas have been investigated in more detail: first, a hilly, bowl-shaped area between dunes with height differences up to 20 metres and a combined sewer system; second, a transition area between a dune area and a flat area with height differences up to 7 metres and a large surcharge of storm water from the old centre by the sewer system; third, a flat area with height differences of less than 1 metre. Since the (closed, no spilling) boundaries of the DEM are far beyond those of the study areas, they are assumed to have no influence on the modelling results in the study areas.

RESULTS

Hilly area 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.

Both modelling techniques show in general flooding at the same locations, although there are some differences for specific locations. For example, the surface flow model 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, the surface flow model computes a water depth of more than 1.20 m at a certain location, although this area is not recognized being vulnerable. The surface flow model simulates a flow path towards this area through an alley that can discharge only a small amount of water. By taking hydraulic constraints 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.

Transition between dune area and flat area

For the transition area, the coupled 1D–2D simulation model simulates considerably more flooding than the surface flow model does (Figure 5 and Figure 6), and its results match experiences in praxis better since it is known that flooding in this area already occurs at rainfall intensities of 20 mm/h. Hence, the assumption that the sewer system has a capacity of 20 mm/h for the area itself is not a valid one. It follows that this area has a large subsurface surcharge from the city centre, and catchments of major and minor system differ strongly.

Flat area

For the flat living area, hardly any differences are visible between the results of the surface flow model and the coupled 1D–2D simulation model (Figure 5 and Figure 7). Both modelling techniques predict a large flooding extent, although only a 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 extent can rapidly increase (Gersorius *et al.* 2011).

CONCLUSION

For the Noordwijk case study, results of the surface flow and coupled 1D–2D simulation models are similar in hilly and flat areas and are confirmed by the municipality complaints database, although there are some differences for specific locations. Surface flow models prove to have sufficient accuracy to get a quick overview of the situation during extreme rainfall.

At the transition between hilly and flat areas, however, the coupled 1D–2D simulation model performs better.



Figure 4 | Depth of water on street in the hilly area between dunes, determined by a surface flow model (left) and a coupled 1D–2D simulation model (right). The dots (shown red in the full colour version of this figure, available online at <http://www.iwaponline.com/wst/toc.htm>) mark vulnerable locations known from the municipality database and the numbers in the left part of the figure correspond with the locations presented in Figure 5.

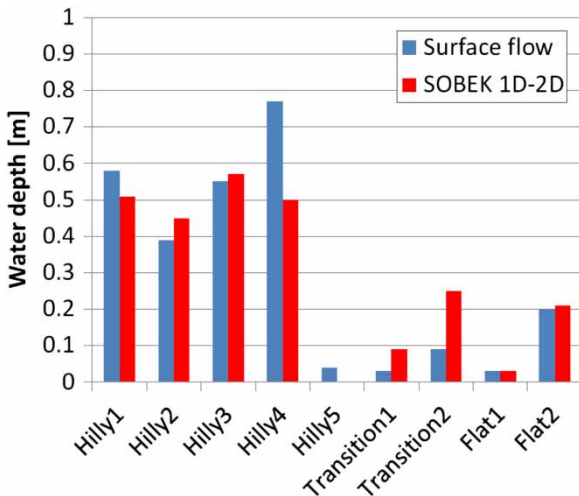


Figure 5 | Maximum water depths for each modelling technique at known vulnerable locations. The numbers correspond with the locations in Figure 4, Figure 6 and Figure 7.

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, locations where catchments of the major and minor system differ are major points of attention since the assumption that the sewer system has a capacity of 20 mm/h for the area itself is not a valid one. The validity of the latter assumption can be checked by the results of sewage calculations that almost every municipality has carried out in the past.

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 surface flow models 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 the 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, which has to be smaller than the typical size of landscape elements; the surface discharge of unpaved areas, which 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 all model results.

Choosing the most appropriate modelling technique means balancing accuracy, computation time, data needs and communication possibilities. The case study confirms practical experiences that surface flow models identify the most vulnerable locations and, hence, their accuracy is

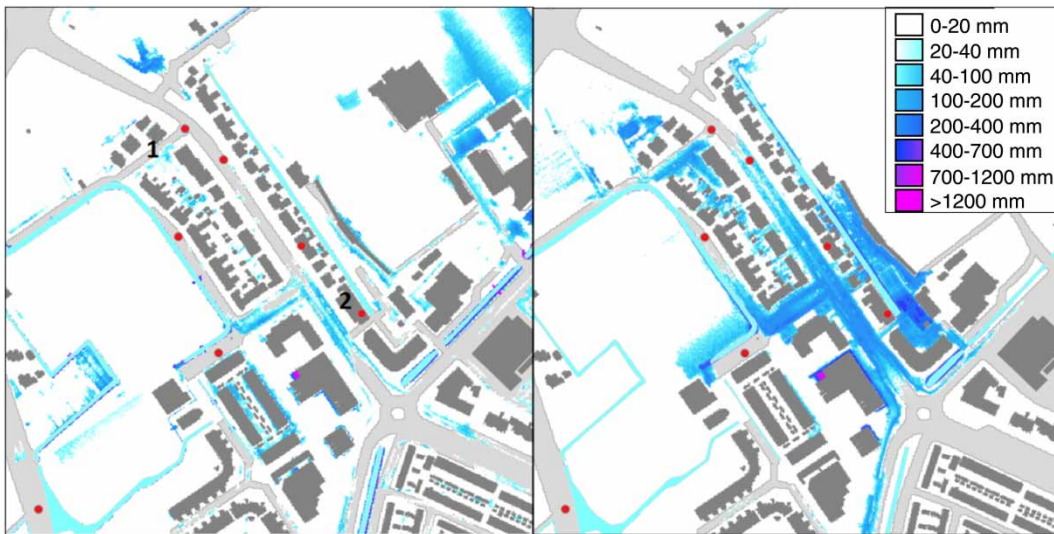


Figure 6 | Depth of water on street in the flat area, determined by a surface flow model (left) and a coupled 1D–2D simulation model (right). The dots (shown red in the full colour version of this figure, available online at <http://www.iwaponline.com/wst/toc.htm>) mark vulnerable locations known from the municipality database and the numbers in the left part of the figure correspond with the locations presented in Figure 5.



Figure 7 | Depth of water on street in the flat area, determined by a surface flow model (left) and a coupled 1D–2D simulation model (right). The dots (shown red in the full colour version of this figure, available online at <http://www.iwaponline.com/wst/toc.htm>) mark vulnerable locations known from the municipality database and the numbers in the left part of the figure correspond with the locations presented in Figure 5.

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. The simulation time with the surface flow model was about an hour for the complete city of Noordwijk. For the case study areas together (approximately 20% of the city), the same simulation took about a day with the coupled 1D–2D simulation model.

Since the most appropriate modelling technique is unknown in advance, a tiered approach is suggested, starting with a surface flow model to get a first insight into the situation and to analyse the effect of possible mitigation measures. For critical locations, an extra analysis of the interaction between the 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.

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