Adaptation tipping points and opportunities for urban flood risk management

SUPPLEMENTARY MATERIAL

Two hydrodynamic models developed with the SOBEK software package were used for this case study. Basic model details are provided here, in supplement to the manuscript.

1-D model

The one-dimensional (1-D) model called DORD_BAS was developed by Luijtelaaet al. (2006) and served to analyze the sewer system. A node-connection schematization was used to model the elements of the sewer network. Two modules of the Sobek software package were used to run the 1-D model: the hydrological RR (rainfall–runoff) open water and the hydraulic 1-D pipe Flow. Figure S1 illustrates the 1-D model structure.

The RR hydrological module is influenced by local rainfall patterns and by the characteristics of the catchment area. Rainfall loads on the sewer system were simulated using the rainfall series ‘Bui6’ developed by RIONED. Bui 6 represents a 1.5 hour distributed rainfall event of 17 mm rainfall depth that occurs once a year (RIONED Foundation 2006). Climate change was simulated by increasing the

Figure S1 | 1-D model structure.
Figure S2 | 1-D/2-D model structure.
rainfall intensity of the design rainfall event. The amount of runoff and the runoff flow rate depend on evapotranspiration, infiltration, interception and retention. These were accounted for by the model builders by using runoff, storage and infiltration coefficients for each type of runoff surface. The runoff area associated with each manhole was calculated by defining Thiessen Polygons (around the nodes that represent manholes) in ArcGIS 10.0.

The hydraulic 1-D pipe Flow module is based on the Saint Venant equations and simulates 1-D flow in the piping system. Most of the load on the piping system comes from stormwater and wastewater. One of the 1-D model outputs was the manhole freeboard height, which allowed determining the percentage of flooded manholes under specific rainfall intensities.

To simulate the current disconnection strategy, the model input file PLUVIUS.3b was modified to reduce the surface area contributing to runoff generation by 40%. Alternatively, land use data can be manipulated in ArcGIS, where imperious surfaces can be changed to pervious surface types if the location and type of disconnection measures are known (such as green roofs and swales). Thiessen polygons can then be recreated around each node and intersected with the new land use file to create a new PLUVIUS.3b input file. This step can be repeated for each urban renewal opportunity in time, and the model can be run with new land use data.

1-D/2-D model

The 1-D/two-dimensional (2-D) model called DORD_ODS was created for this research, and served to simulate interactions between the minor and the major overland drainage systems. The 1-D/2-D model simulates runoff flows, 1-D channel flow and 2-D overland flow. As shown in Figure S2, three modules of Sobek are used to run the 1-D/2-D model: the RR open water, the 1-D pipe Flow,
and the 2-D Overland Flow. The 2-D Overland Flow module simulates water conveyance above ground.

For the 2-D Overland Flow module, a land cover map with corresponding roughness coefficients was obtained from the Water Board Hollandse Delta. Moreover, the Municipality of Dordrecht provided the digital elevation map (DEM) ahn2 in raster format, with a resolution of 0.5 × 0.5 m. Because of software limitations (Sobek), the ahn2 map was ‘reshuffled’ in ArcGIS so as to obtain the 2 × 2 m resolution map. Moreover, since the buildings and trees were removed from the original ahn2, the terrain at those locations was approximated by inverse distance weighted interpolation, using 12 neighboring cells (this is the digital terrain model (DTM)). It is important to use the DTM in which all cells have a value, instead of the DEM in which buildings and trees have no assigned value, so that the water can reach those areas (buildings) during the model simulation.

The land cover map containing roughness coefficients and the DTM were overlaid in ArcGIS 10.0 and converted into an ASCII file which served as input file to the 2-D Overland Flow module. The 1-D/2-D model output provided the maximum water depth and flow direction, which allowed determining which building blocks were flooded (assuming a 5 cm doorstep height).

The development of adaptation measures for the alternative strategy (such as increased curb height and additional speed bumps) was based on the flow patterns of the model runs with the current terrain.

**SENSITIVITY ANALYSIS**

The tipping point analysis was performed for 0% and 5% performance thresholds as shown in Figures S3 and S4, respectively.
LIMITATIONS

One of the drawbacks of this study was the use of the Sobek software package to simulate overland flow. Sobek uses a very high volume of a computer's virtual memory and can only use one processor at a time. This limited the amount of information that could be processed to areas of 100–400 hectares, with a resolution or cell size of 2 × 2 m. The non-linear processing time took between 1 and 10 days per simulation. Moreover, breaking up the 1-D/2-D simulations per district gives invalid results at the district boundaries on which one cannot conclude. Another limitation regarding the analysis performed is the assumption that all buildings have a doorstep height of 5 cm. This assumption is rather conservative; however, results could certainly vary if the exact doorstep height of each building was used instead. Additional limitations for the 1-D model are available in Luijtelaar et al. (2006).

REFERENCES
