Integrated Flood Risk Analysis
and Management Methodologies

Flood Inundation Modelling

EXECUTIVE SUMMARY

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SIXTH FRAMEWORK PROGRAMME

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CONTENTS

Executive Summary for Task 8

1. Scope of the research in Task 8

1.1 Problem definition

In situations of flood risk, authorities need to make decisions concerning the management and evacuation strategies to apply. However, in order to prepare evacuation plans, or to assess potential damage, information is needed on inundation patterns, including water depths, flow velocities, and timing of inundation. This information can be derived using inundation models, i.e. computer programs that simulate inundation along rivers, coasts or even urban drainage systems.

The outcome of inundation models also is required for long-term planning. Long-term planning is an integral part of developing sustainable flood risk management polices and intervention measures. In particular, it enables decisions makers to explore strategies, set targets, question the status quo, and to determine the merits of innovative ideas. Flood inundation models are essential in the development of a framework for long-term planning of flood risk management.

Finally, inundation modelling also is essential for flood event management. Plans for warning, evacuation and traffic routing often are based on computed flooding patterns, water depths and arrival times of the flood water (FLOOD***site*** Task 17, 19 and 23).

Different types of inundation models exist. In certain situations one may not even need a model at all to predict inundation extent. Given gauged water surface elevations along a reach, or water surface elevations predicted on the basis of flood frequency analysis, one can perform a similar interpolation to that used by Werner (2001; 2004). This approximates the flood wave as a plane (or series of planes) which are intersected with the DEM to give extent and depth predictions. In other cases, one dimensional (1D) models are applied (Figure 1.1). Here, floodplain flow is treated as one-dimensional in the down-valley direction. In case of large polder areas or more complex floodplain topographies, 1D models are used in a quasi 2D mode (Figure 1.1). Two-dimensional (2D) models, coupled 1D-2D models or even tree dimensional (3D) models can be applied as well.

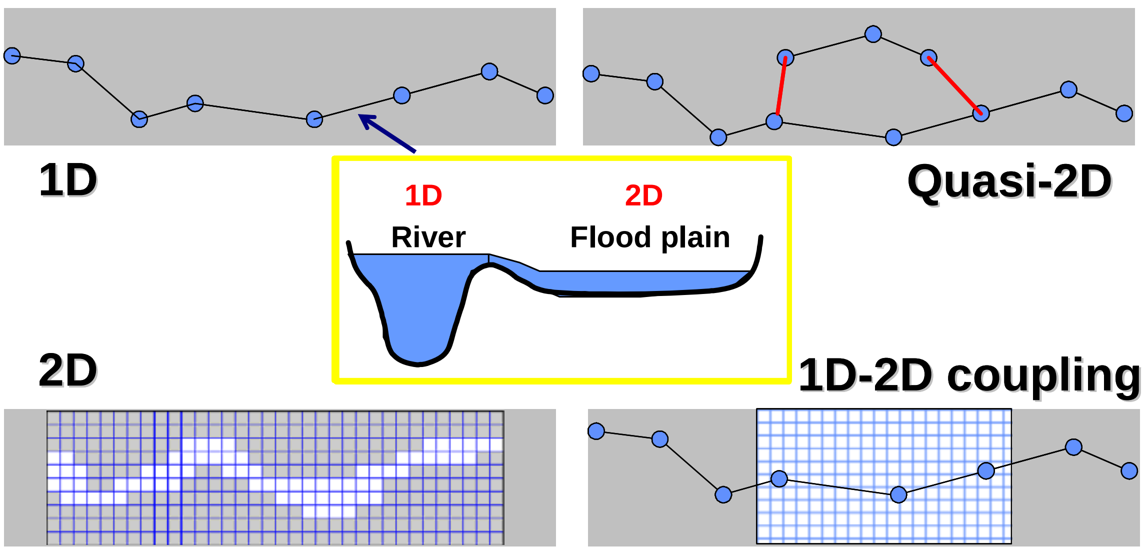


Figure 1.1 Types of numerical models used for inundation modelling

For non experienced modellers it often is difficult to determine what type of model they should apply. And even if the right model choice is made, it can remain difficult to apply the model in a proper way. Questions that often arise concern the grid cell size to be used in case of a 2D model, the processes that should be included (such as breach growth, wind effects and evaporation), or the best way to schematise a complex area.

1.2 Objective

The main objective of Task 8 therefore was to develop guidelines on:
1. the type of inundation model that should be applied depending on the type of area under investigation and amount and accuracy of the available input data;
2. how the models should be applied properly.

1.3 EU Directive on the assessment and management of flood risks

The EU Directive on the assessment and management of flood risks (2007/60/EC) from 26 November 2007 (European Commission, 2007) obliges the EU member states to – amongst others - develop flood risk maps. In areas where data on floods are scarce, inundation models are indispensable. However, in order to obtain reliable flood risk maps it is important that a proper type of inundation model is selected and that the models are applied properly. Task 8 supports flood risk managers in the selection and application of inundation models.

1.4 Position of Task 8 in FLOODsite

FLOOD***site*** consists of several Themes. Theme 1 of FLOOD***site*** provides new knowledge and understanding to derive risk analyses for flood prone areas. To obtain these objectives a possible design concept is suggested. This concept is based on the FLOOD***site*** risk-source-pathway-receptor approach.

Risk sources (Sub-Theme 1.1) describe the sources of risk (such as storm surges, river discharges, heavy rainfall or combinations of those). Risk pathways (Sub-Theme 1.2) describe the way risk travels from the source to the receptors. It includes loads and resistances of flood defences, failure modes and limit state equations of defence elements and the inundation process. Finally, risk receptors describe who is receiving the risk (such as people living in flood prone areas, properties, etc.). It also deals with ecological impacts and risk reception.

Task 8 is part of Sub-Theme 1.2. The links between Task 8 and other relevant tasks is given in Figure 1.2.

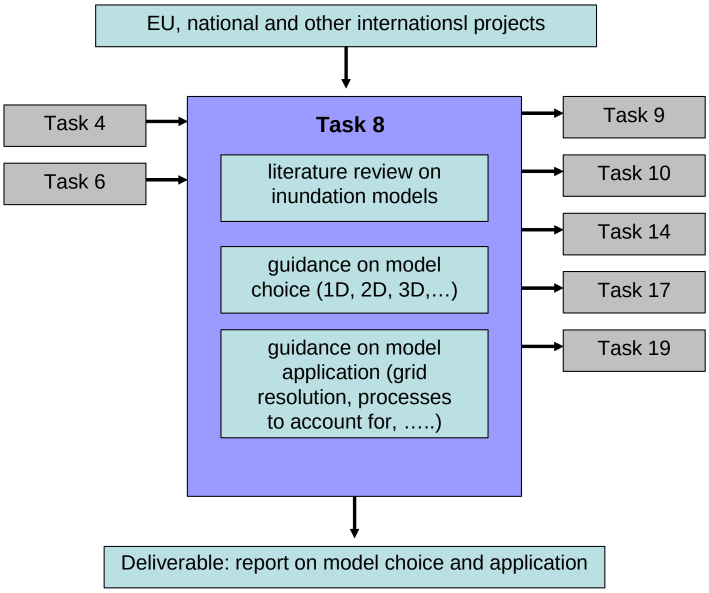


Figure 1.2 Interaction between Task 8 and other tasks in FLOODsite

2. Approach

Task 8 addresses two questions:

1. what type of inundation model should be applied depending on the type of area under investigation and amount and accuracy of the available input data?
2. how should the model be applied properly?

As part of Task 8, different types of inundation models were developed or used for the same pilot site. The model results were compared and the advantages and disadvantages of each model were described (results are shown in section 3). Based on this analysis, guidelines were developed to determine what type of inundation model should be used, depending on the type of area and the available input data.

The selected pilot sites comprise a dike ring area bordering the Scheldt estuary in the Netherlands, a site along the Thames estuary in the UK, and part of a steep mountainous river in Italy (the Brembo river). The main differences between the two sites are listed in Table 2.1.

Table 2.1 Characteristics of the selected pilot sites

	Scheldt	**Thames**	**Brembo river**
Size	82 km²	11.5 km²	50 km
Topography	Relatively flat polders, separated by secondary dikes and protected by coastal embankments designed to protect against the 1 in 4000 year flood	Relatively flat. Floodplain lies behind river embank-ments designed to protect against the 1 in 1000 year flood.	Steep mountainous river. The river bed presents a lot of steep and adverse slopes. Cross sections present successive enlargements and constrictions.
Minimum elevation	1.5 m below sea level	-5.36 mAOD	480 m
Maximum elevation	1.7 m above sea level	101.3 mAOD	130 m
Land use	rural, with some villages	Urban, consisting of a mix of housing, light industry and major structures (e.g. the Millennium Dome)	alternation of rural and urban areas

Table 2.2 shows the type of models that were developed for each of the selected case study areas. The software packages mentioned in Table 2.2 are described in more detail in the final report of Task 8 (document T08_09_03). A more thorough review on inundation models was reported by Woodhead *et al.* (2006)

Table 2.2 Applied inundation models

Model type	Scheldt	Thames	Brembo
1D			SOBEK 1D[1], SV1D², SANA[5], ORSA1D-Roe[5]
1D in quasi 2D mode	SOBEK 1D[1]		
pseudo 2D (no time stepping)		RFSM[4]	
2D	SOBEK 2D[1], SV2D²	SOBEK-2D[1], LISFLOOD-FP[3], Infoworks2D[4]	

Simulations carried out by [1]Deltares|Delft, ² UCL, [3] Uni Bristol, [4]HRW, [5]Pavia University

Next, the models are used to assess the impact of different model schematisations and processes on the model results. The outcome of this analysis was used to develop guidelines on how to apply the inundation models properly.

The Thames model was used to assess the impact of:
- grid cell size of the elevation model;
- schematisation of buildings;
- changes in hydraulic roughness;
- the impact of wind;
- accounting for tunnels underneath the Thames.

The Scheldt model was used to determine the impact of:
- variations in breach growth rates;
- wind set up (most models do not account for wind effects);
- schematisation of buildings;
- resolution of the elevation model;
- variations in boundary conditions.

No sensitivity analyses were carried out with the model of the Brembo river.

3. Principal results

3.1 Analysis based on models for the Scheldt pilot site

3.1.1 The Scheldt model

The inundation model for the Scheldt pilot site was made using laser altimetry data with a resolution of at least 1 point per 10 m². The elevation of embankments and secondary dike were provided in more detail by local water boards. The model was used to simulate the 1953 flood that struck the south western part of the Netherlands, including this pilot site. Figure 3.1 shows the flooding patterns that were observed during this flood as well as the water depths that were computed with the SOBEK model for the same event. The SOBEK model had a 50 m resolution. Breach locations and breach widths applied in the model were identical to those observed in 1953 (indicated by the black arrows in Figure 3.1a).

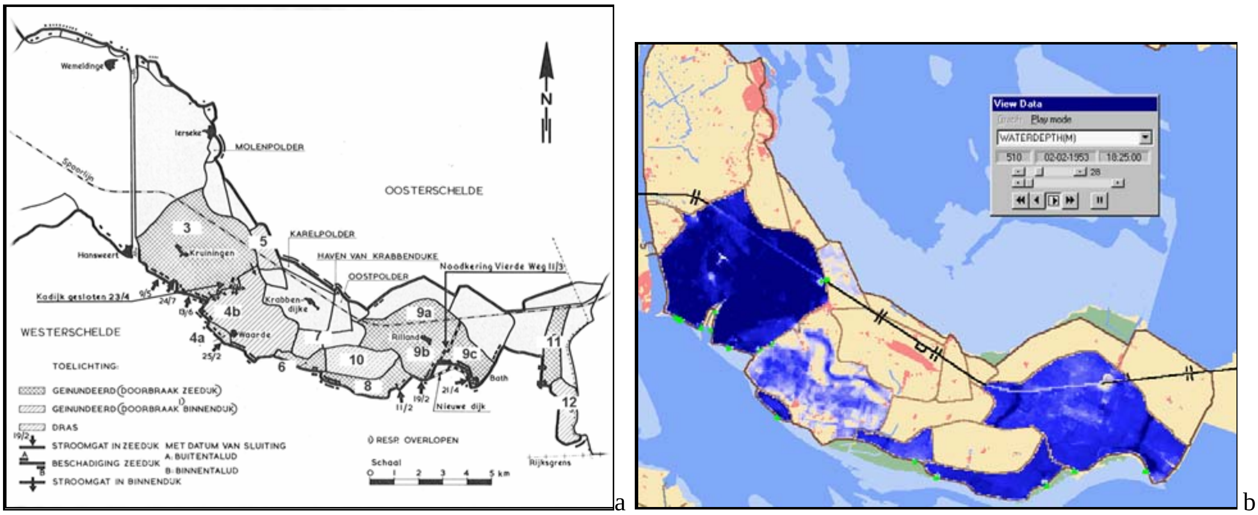


Figure 3.1 Observed flooding patterns during the flood of 1953 (a) and water depths computed with SOBEK (2D)(b) (source figure a: Rijkswaterstaat and KNMI, 1961)

3.1.2 Comparison of SV2D and SOBEK-2D

SV2D and SOBEK-2D produce very similar results for the Scheldt pilot site (see for instance Figure 3.2). The differences mainly occur during the first tidal cycle, in the beginning of the simulation, and are related to the way breach growth is being simulated. Instantaneous breaching is assumed in SV2D-inst. This results in a very rapid rise in water level. SOBEK and SV2D-prog assume the breach grows more gradually in time. During subsequent tidal cycles, when the breach is open in all simulations, computed water levels and flow velocities are more or less identical.

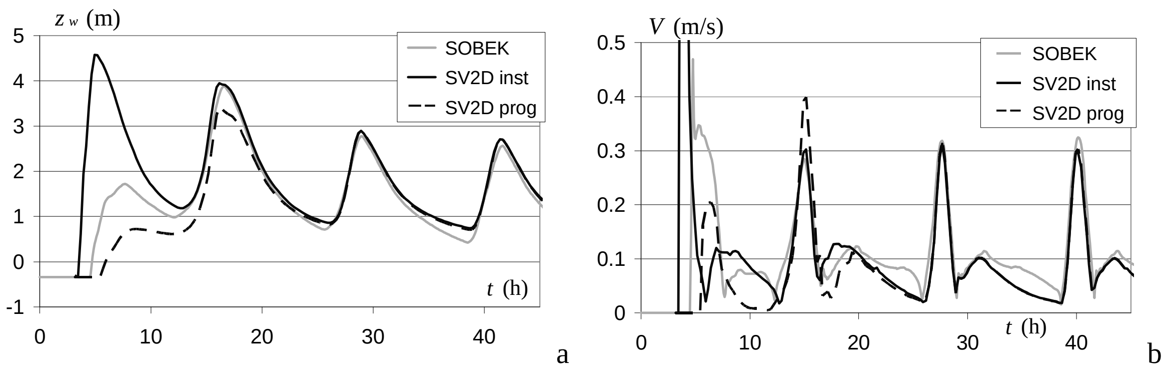
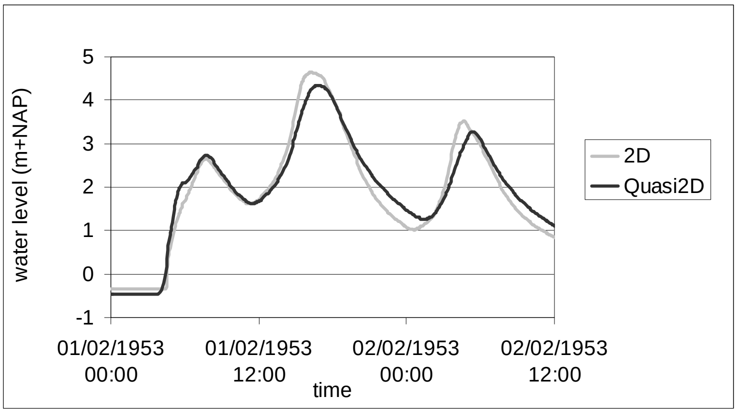


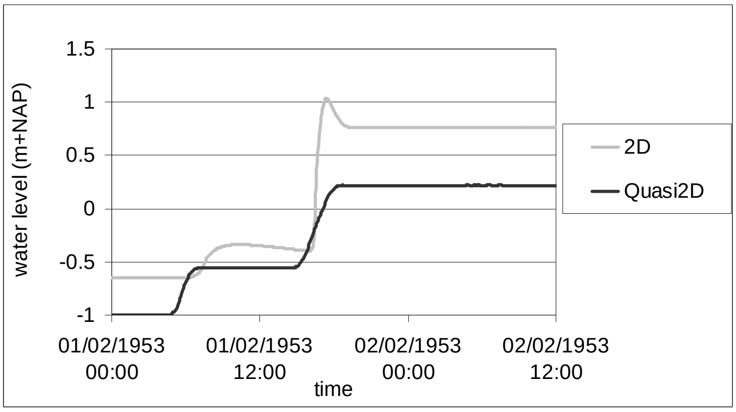
Figure 3.2 Computed results in polder 3 (Figure 3.1a): (a) water level and (b) velocity

3.1.3 Comparison of 2D and quasi 2D approach using SOBEK

Much larger differences are found between the 2D and quasi 2D application of SOBEK in the Scheldt pilot site. For locations that are situated close to the dike breach, the results are quite similar (Figure 3.3a). For locations that are separated from the breach by a secondary dike very different results are obtained (see Figure 3.3b).



a



b

Figure 3.3 Water levels (m +NAP) computed with the 2D and quasi 2D application of SOBEK for polder 3 (a) and polder 4b (b) (for locations see Figure 3.1a)

The main reason for the differences in polders that are separated by a secondary dike seems to be related to spatial differences in flooding in the first polder behind the breach. This is simulated in greater detail in the 2D model than in the quasi 2D model. This is explained in Figure 3.4. The upper part of Figure 3.4 represents 3 polders that are separated by secondary dikes. The green and red lines represent relatively low sections in the secondary dikes. The green section is lower than the red section. If the primary dike fails at the location represented by the black line it is very likely that water will first flow over the low section indicated by the red line. This will be simulated by the 2D model. Hence, according to the 2D model, polder B will be flooded before polder C. However, in the quasi 2D model, this spatial effect in polder A is not accounted for and water will start flowing over the lowest section in any of the surrounding dikes. Thus, according to the 2D model, polder C will be flooded before polder B.

The results of this comparison thus indicate that quasi 2D models can only successfully be applied if the flow pattern is known in advance, so that the model schematisation can be adjusted to it. This implies that quasi 2D models can relatively successfully be applied to river systems where the flow directions are known in advance. Application to relatively flat areas, where flow patterns may differ depending on the breach location, or where flow patterns are not very obvious, is likely to result in very inaccurate results.

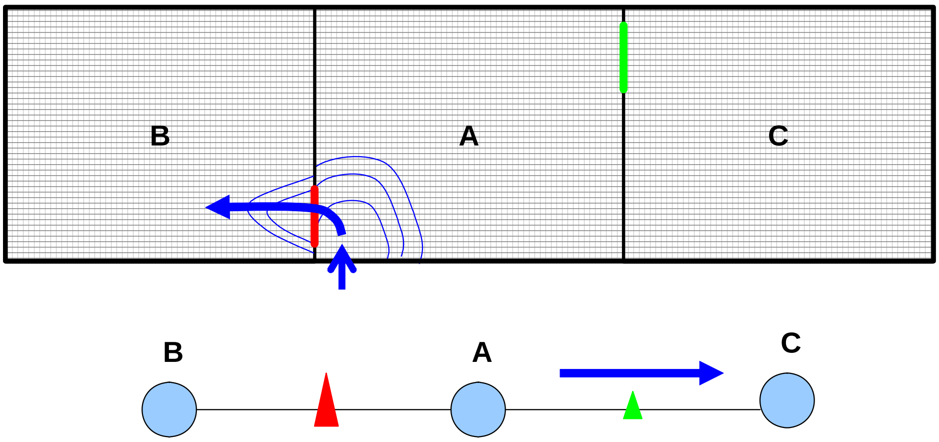


Figure 3.4 Schematisation of 3 polders in 2D (upper half) and quasi 2D (lower half). Red and green lines represent low sections in secondary dikes between the polders. The green section is lower than the red section.

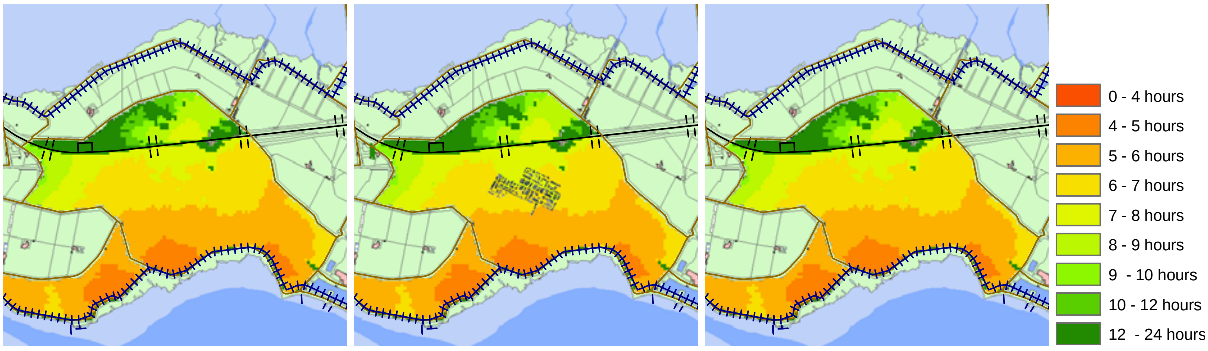
3.1.4 Impact of buildings on inundation patterns

Most studies that aim at determining the maximum grid cell size to be used in inundation models for urban areas look at densely populated areas. In those models a large part, if not the entire model area is urbanised. The conclusion of these studies often is that the maximum grid cell size should not exceed 10 m (see also chapter 3.2.4) as for European cities this is often the minimum gap distance between building. Grid sizes larger than this can artificially close routes for flow..

The Scheldt pilot area consists of a rural polder area in which small villages are present and the required results regard the spreading of the flood within the polder. Analysis were carried out to determine if a grid cell size of less than 10 m is required to simulate the flooding process with sufficient detail. Three models were made:
1. a relatively coarse grid (50m x 50m) in which buildings were schematised by increasing the hydraulic roughness of the entire urban areas;
2. a fine grid in which buildings were schematised as solid 2D objects;
3. a fine grid in which the hydraulic roughness in streets was reduced and the roughness at grid cells that coincide with buildings was increased.

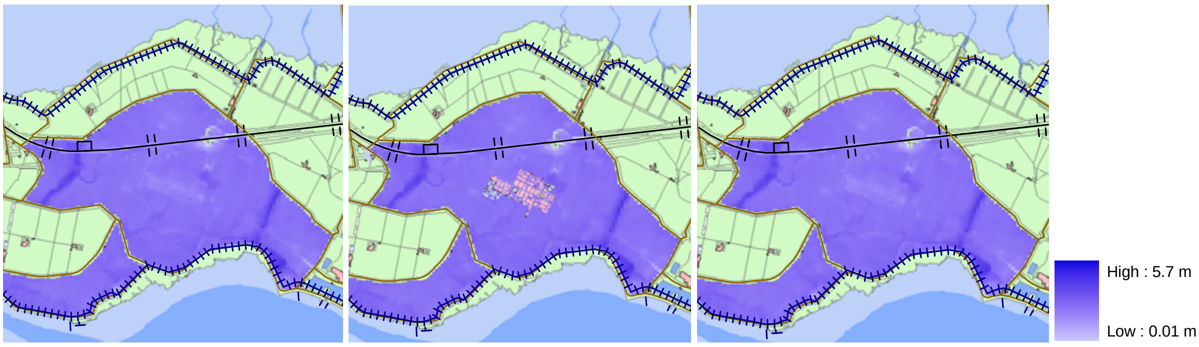
No differences in time of inundation were found between the models (Figure 3.5). Computed water depths also were equal (Figure 3.6). The only differences that were observed related to the flow velocities in the streets in the villages (Figure 3.7).

The main conclusion therefore is that if the user is interested in the flooding pattern that occurs in a rural area and the water depths that occur in villages, a coarse grid with grid cell sizes of more than 10 m is of sufficient detail and buildings do not have to be accounted for in the model schematisation, other than by changing the hydraulic roughness. The maximum grid resolution depends on the topography. In relatively flat areas with smooth topographies a grid resolution of 100 m is fine, whereas in areas with an irregular topography a resolution of 50m can be too coarse. Only if the user is interested in flow velocities in the villages, smaller grids are needed and buildings should be schematised.



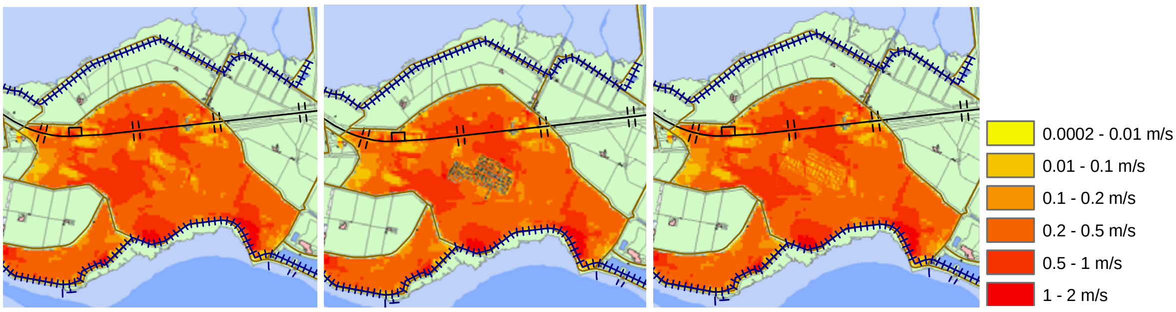
a b c

Figure 3.5 Moment of first inundation computed a coarse grid (a), a finer grid and solid buildings (b) and a finer grid with very high roughness values representing buildings (c)



a b c

Figure 3.6 Water depths computed with a coarse grid (a), a finer grid and solid buildings (b) and a finer grid with very high roughness values representing buildings (c)



a b c

Figure 3.7 Flow velocities computed with a coarse grid (a), a finer grid and solid buildings (b) and a finer grid with very high roughness values representing buildings (c)

3.1.5 Impact of wind on inundation patterns

Most inundation models do not account for the impact of wind. However, coastal flooding mainly occurs during storm surges, when strong winds prevail. Therefore, a number of calculations with the SOBEK (2D) model of the Scheldt were made with different wind situations, changing the direction as well as the wind speed, in order to see the effect on the outcome of the calculations. Wind friction is accounted for in the momentum equation in SOBEK.

Figure 3.8 shows the difference in computed water depths. In polders that are flooded through one or more breaches in the primary sea defence system, changes in water depths of about 0.3 m occur (10% change). However, when polders are flooded through a breach in a secondary dike, an increase in water level of about 0.65 m may occur when the polder is located downwind of the breach (more than 50% increase).

It is therefore concluded that wind can have a significant impact on computed water depths. The wind set up depends on the fetch length. In this case the fetch length is about 5 km. The larger the polder, the longer the fetch length, which results in a higher wind set up. Flow velocities do not change much due to strong winds. The time of inundation (hours after failure of the coastal dike) is also hardly effected by wind. Only when the progress direction of the flood wave is in the same or opposite direction of the wind direction the time of inundation is affected by wind, but still not very significant. This effect may however be stronger when larger areas are flooded than the polders in this pilot site.

Other meteorological factors, such as evaporation, have no significant effect on flooding simulations for the Scheldt, because the probability for flooding is highest during the winter season, when evaporation values are very low. However, in other areas evaporation can be an important process as well. This often is the case in extensive wetlands, where flooding occurs during the summer season, or that are located in a warmer climate. An example of such an area is the Doñana wetland in Spain. Here flooding occurs during the winter season. During the summer period, the wetland dries up, partly because water drains to an adjacent river, but for the main part because of high evaporation rates, which vary from 5 to 14 mm per day during the summer months. Measured evaporation rates indicate a total evaporation of about 0.7 m during the period April - July.

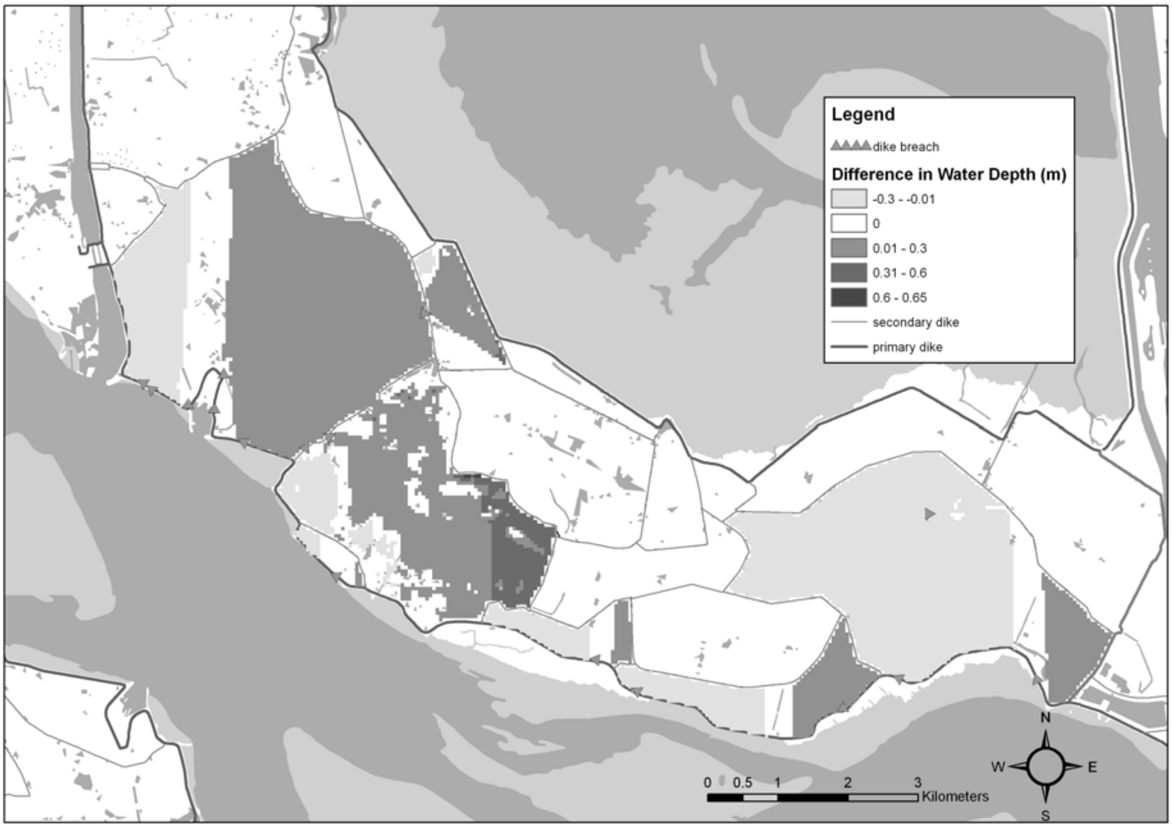


Figure 3.8 Difference in water depth (m.) between the simulation with wind force 10, direction west, and the simulation without wind

3.2 Analysis based on models for the Thames pilot site

3.2.1 The Thames model

The inundation model for the Thames pilot site was made using LIDAR data collected at 1 m resolution. From this data set, two types of elevation models were made:

1. With houses as 2D objects
2. Without houses (houses and other objects were filtered out of the data)

Also, elevation models were made with grid cell size varying from 2 to 50 m.

Unlike the Scheldt pilot site, where flooding was caused by widespread breaching, flooding in the Thames embayment is expected as a consequence of overtopping of the flood defence. The overflow simulations that provided the inflow volumes used in the flooding simulations, were performed by HR Wallingford Ltd (Gouldby *et al.*, 2007).

3.2.2 Comparison of LISFLOOD-FP and SOBEK

Notable differences between the results of SOBEK and of LISFLOOD-FP are (see also Figure 3.9):

- Difference in maximum depth of both models is varying per location (at some locations differences are only a few percent, whereas at other locations differences can be more than 50%);
- Some parts do flood in SOBEK and not in LISFLOOD-FP and vice versa;
- The flood propagation is generally quicker in LISFLOOD-FP;
- SOBEK runs the simulations much faster than LISFLOOD-FP (a high resolution 5 m grid and a 50 minute simulation period takes several minutes to be simulated in SOBEK, but several days to be simulated with LISFLOOD-FP. This difference decreases when larger grid cell sizes are applied).

Figure 3.9 Difference in maximum water depth computed with SOBEK and LISFLOOD-FP (blue means that LISFLOOD is deeper, yellow or red means that SOBEK computes larger depths)

One of the reasons for these differences seems related to the fact that SOBEK is able to model inertia, while LISFLOOD-FP is not. When water overflows the embankments along the Thames, it plunges into the street. This results in a sort of wave that may overtop obstacles in or along the street. SOBEK is able to simulate this "plunging" effect. LISFLOOD-FP can not simulate this plunging effect. Hence, according to the LISFLOOD-FP model, no water can flow over obstacles that exceed the elevation of the equilibrium water level.

3.2.3 Effect of grid size

Figure 3.10 shows an example of the differences in flooded area computed with the SOBEK model using a fine and a coarse elevation model (5m and 25 m grid cells). Results indicate that a proper representation of a densely built up area, such as this area along the river Thames, grid cell sizes should generally not exceed the size of 10 m, but preferably 5m or less. With larger grid cells, streets are schematised less accurately and less continuously. This may result in errors.

Figure 3.10 The flooded area in the 5 and the 25m grid cell size, computed with the SOBEK model. The 5m grid is on top and represented by the brown colour. The 25m grid is in green, which represents the calculated water depth.

It is concluded that the grid resolution in densely built up areas should not exceed the size of the streets which for most European cities are in the order of 10 m. Preferably a grid cell size of 5m or less should be applied to prevent 'blockage' of streets in the elevation model.

3.2.4 Effect of buildings on simulated flow patterns

The exclusion of the buildings in the model has a big effect on the spreading of the flood. At some locations, especially near the Millennium dome (near the 'circle' in the upper part of the study area in Figure 3.10), the flood spreads much further inland with buildings than without buildings, maybe because of reduced storage in case the buildings are simulated as solid blocks. At other locations the flood reaches less far inland when buildings are included in the model schematisation. This is partly because the street-level is not well presented in the model that includes buildings, thus blocking the flow-path of the flood-wave and partly because water flows more easily through a wide channel (no buildings) than through a small channel (such as streets when buildings are included). Figure 3.11 shows an example of computed water depths.

Figure 3.11 Flooded area for the 5m grid with buildings (brown) or without buildings (green), computed with the SOBEK model.

The schematisation of buildings as 2D solid objects results in preferred flow through streets as long as the grid resolution is smaller than the width of the streets. At coarser resolutions the 2D buildings only obstruct the flow and prevent the flood wave from spreading inland.

3.2.5 Hydraulic roughness

The impact of obstacles, such as vegetation or boulders, that obstruct the flow, is accounted for by the hydraulic roughness. The SOBEK model was used to analyse the impact of changes in hydraulic roughness values on flood characteristics. For this analysis, the hydraulic roughness was increased from manning = 0.035 (typical for grass and row crops) to manning = 0.07 (typical for moderate to dense brush, or heavy stand of timber with few down trees). This increase had the expected effect of slowing down the proceeding of the flood-wave, but seems to have a smaller effect than increasing the grid-size from 5 to 10m.

3.3 Analysis based on models for the Brembo river

3.3.1 The model of the Brembo river

The Brembo is a 50 km long river situated in Nothern Italy, in the Lombardy Region. It springs from the Bergamo Alps, then is fed by some water courses, and flows into the Adda river at the border between the provinces of Bergamo and Milan (Figure 3.12). The bed of the Brembo river presents a lot of steep and adverse slopes, and the cross sections present successive enlargements and constrictions. This makes hydraulic modelling a real challenge.

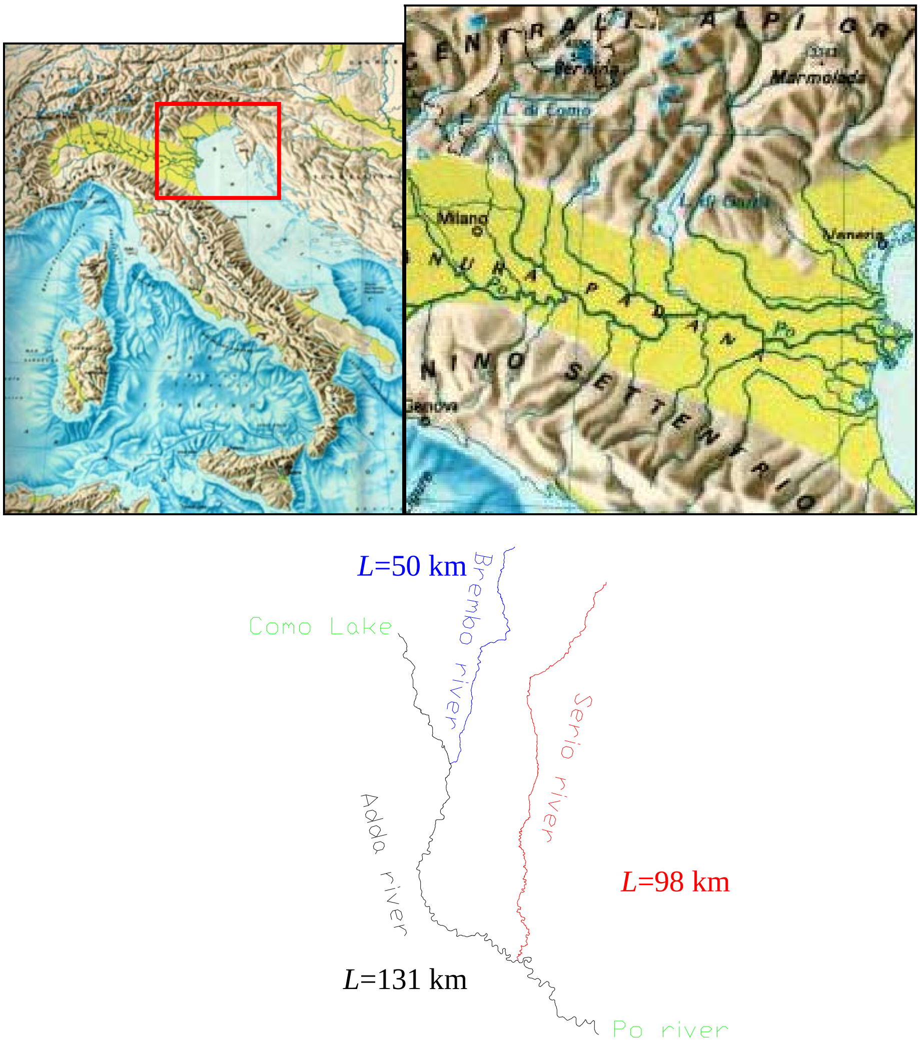


Figure 3.12 Location of the Brembo River in the Italian Alps and plan view of the Brembo River with the major tributaries of the Adda river

The data were provided by the research unit of Pavia University, coordinated by Prof L. Natale, and consisted of model input data (topography of the area, and the upstream hydrograph) and model validation data (measured water levels at several locations along the river). The topographical data used for the hydraulic models comes from a field survey and provides one-dimensional cross-sections, with an average spacing of less than 200 m.

Four 1-dimensional models were developed using the following packages:

- SOBEK-1D;
- SV1D;
- ORSA1D-Roe;
- SANA 1D.

A description of the models is given in the final report of Task 8 (Asselman et al., 2009).

3.3.2 Comparison of SV1D, SOBEK-1D, ORSA1D-Roe and SANA-1D

Figure 3.13 through Figure 3.16 show the computed maximum water depths during the flood of June 1996. Observed water levels are shown for comparison. In general, the models underestimate maximum water levels. This mainly is caused by the fact that no data were available on the discharge supplied by the tributaries (e.g. in reality the discharge increased in a downstream direction whereas the models assumed no lateral supply of water occurred).

The models compute very similar water levels for most locations along the Brembo river. However, differences in computed water levels are much larger at locations characterised by large variations in river bed slope and/or large variations in channel width. See for instance the 6 meter difference in computed water level between km 24 and km 25 (Figure 3.14).

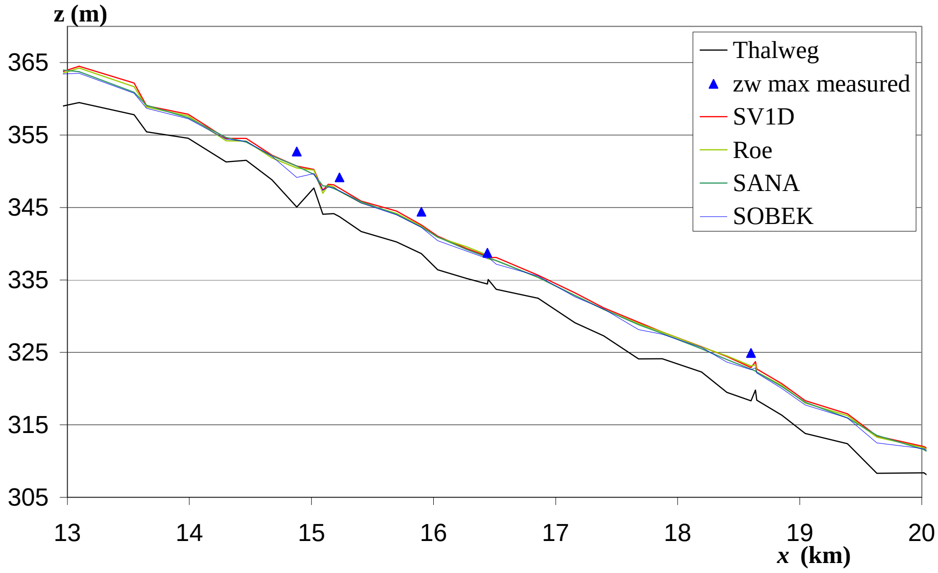


Figure 3.13 Simulated and measured maximum water levels between x = 13 km and x = 20 km

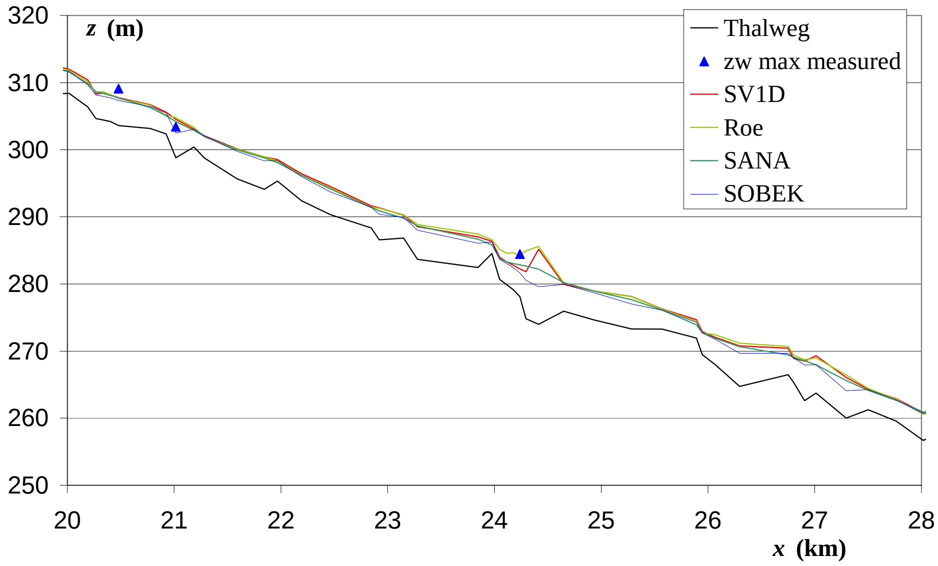


Figure 3.14 Simulated and measured maximum water levels between x = 20 km and x = 28 km

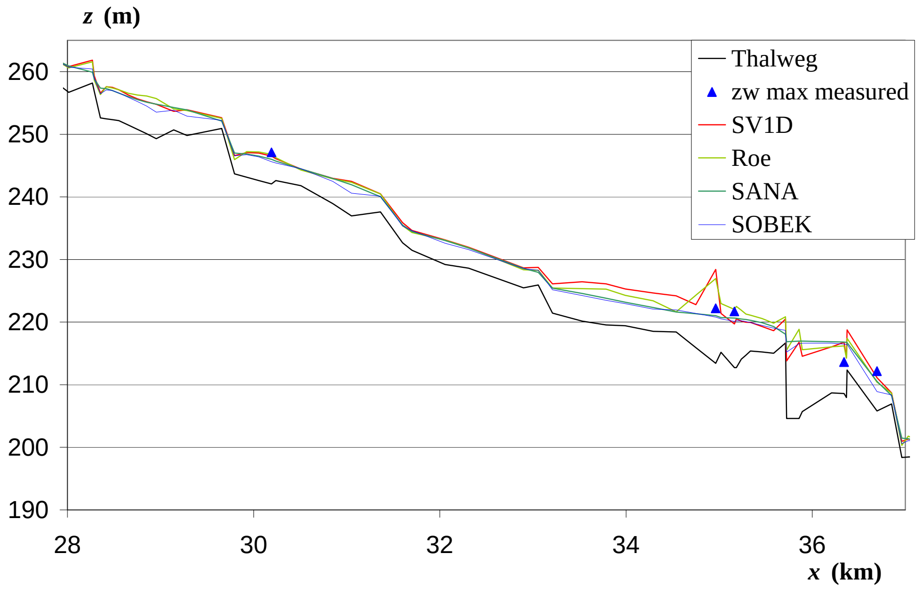


Figure 3.15 Simulated and measured maximum water levels between x = 28 km and x = 37 km

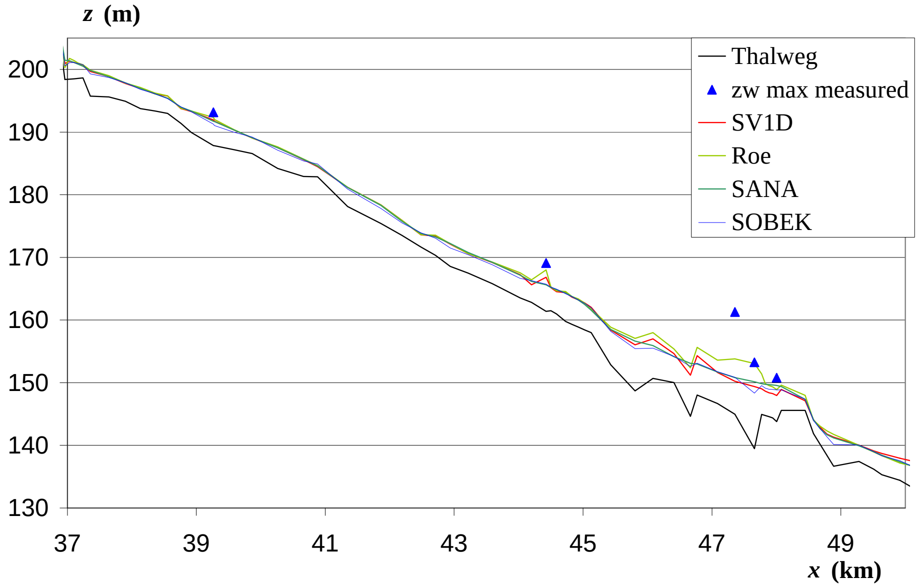


Figure 3.16 Simulated and measured maximum water levels between x = 37 km and x = 50 km

One of the reasons for the large differences concerned the resolution of the model discretization. The data showed an important widening of the cross section just after km 24. After performing steady-flow simulations, it was observed that flow in this area should be close to the critical depth, but always subcritical. The erroneous results of SV1D and ORSA1D-Roe were thus suspected to be due to the too coarse description of the topography. Therefore, based on steady-flow simulations, a convergence study was performed: additional cross-sections were interpolated in this area to refine the computational grid locally. The new results for Orsa1D-Roe and SV1D with the interpolated cross sections indicated lower water levels, without any sudden elevation of the water level. SOBEK interpolates the cross sections automatically when the number of calculation points exceeds the number of cross sections.

Other possible reasons for the differences are related to:

1. differences in the way cross sections defined by yz-coordinates are used by the software package (Figure 3.17);
2. the way interpolation between cross sections is carried by the software package. Many models compute water levels at the cross sections, whereas flow velocities are computed for locations between the water level points. In this case the cross section either upstream or downstream of the reach can be used. In situations with rapidly varying cross sections, such as is the case in the Brembo river, this may cause errors. SOBEK also interpolates the cross sections to the location where the velocity is computed. A sensitivity analysis for the Rhine model showed that this new approach resulted in water level differences of 30 cm. Given the large variability in the cross sections in the Brembo river, differences could be even larger here.

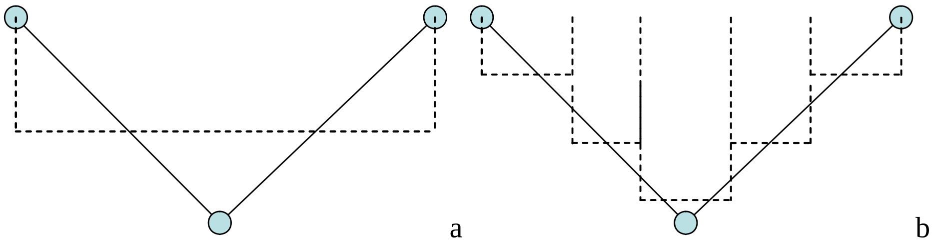


Figure 3.17 Schematisation of yz-cross sections (blue dots are yz points given by the user, the bold line represents the actual cross section and the dotted line the cross section used by the model

Simulation of a flood in a steep mountain reach requires a particular attention to the way the terms representing the topography (the source terms) are represented and discretised in the numerical scheme. Especially, it was shown that in some models a too coarse discretisation in areas where the topography shows strong variations may lead to erroneous results. Interpolation of cross sections is required.

3.4 Conclusions

Only a limited number of software packages were used in this study. However, based on the results of these models we tried to produce a more generic overview of the type of hydraulic models that can be used depending on the characteristics of the area and on the available data. This overview is given in Table 3.1. More information on different types of models can be found in the final report of Task 8.

Table 3.1 Overview of hydraulic model types and their application

Area characteristics	examples	data	applicable models
Wide, relatively flat areas with natural or agricultural land use	low land rivers with wide floodplains, river delta's, estuaries with large flood plains	detailed data available (laser altimetry terrain data, channel bathymetry infor-mation, land use data, accurate boundary condi-tions. Data for model validation)	2D models with structured or unstructured grids. Storage-cell approach also usable if limited discharge through the floodplains (mainly storage)
		detailed topographical data missing	1D model with approximate storage cells
Steep sloping rivers with large floodplains		detailed data available	2D models coping with transcritical flows
		detailed topographical data missing, cross sections available	1D models coping with transcritical flows and preferably shock-capturing
Steep sloping rivers with narrow floodplains			1D or 2D models coping with transcritical flows If available, 1D model with mass and momentum exchanges between subsections
Urban areas	cities along rivers, estuaries or coasts	detailed data available (laser altimetry terrain data, digital map data, accurate boundary conditions. Data for model validation)	2D models, with full shallow water models where local inertial effects are important. 2D storage cell models currently give reasonable results but at high computational cost.

With respect to model application the following guidance is given:

- Grid and time step resolution: When developing a model for a particular site, choices also need to be made about the discretization of space and time. These will clearly depend on the resolution of available terrain data, the length scales of terrain features in the domain and the length and time scales of relevant flow processes. Grid resolutions in rural areas with a gentle/regular/… topography can be coarser than grids developed for areas with a more complex topography or urban areas. The minimum grid resolution that is required for flood simulations in urban areas depends on the characteristics of the city (e.g. size of the streets) and on the required information. In general, less resolution is required if only water level is to be predicted, finer resolution if the velocity field is also required for flood characterisation. In particular, in urban areas, if the user is interested in water depths only, the minimum grid cell size should equal half to once the width of the streets (e.g. 5 to 10 m in most European cities). In rural areas where villages make up a small part of the total model area, larger cells can be used, e.g. grid resolutions of 50 to 100 m are quite common in the Netherlands. Water depths in urban areas can also be computed quite accurately by increasing the hydraulic roughness or by adopting a porosity approach (for more information see the final report of Task 8). When information on flow velocities is required, the grid cell size should always be smaller than the width of the streets. This requirement applies to vast urban areas as well as for small rural villages. Increasing the hydraulic roughness or application of the porosity approach does not result in accurate velocity estimates.
- The timing of breach initiation and the breach growth rate determine to a large extent the volume of water that flows into an area. This implies that breach initiation and growth have a very large effect on computed water depths and flood extent. Unfortunately, breach initiation and growth are difficult to forecast and simulate, due to the complex mechanisms involved and to the stochastic character of breaching initiation. The advice therefore is to always carry out a sensitivity analysis to determine the uncertainties in the model results related to uncertainties in breach initiation (timing) and growth rate. The latest science on breach growth is reported in the final report of Task 6 (Report T06-08-02).

- Wind effect: In open areas, such as flood plains used as grass land or polders used for agricultural purposes, water depths can significantly be affected by wind. In open areas with fetch lengths of about 5 km, wind set-up during storms can be in the order of 0.5 m. Wind has less effect in large urban areas. The pilot site along the Thames estuary indicated changes in water depth in the order of 5 cm or less.
- Hydraulic roughness: Hydraulic models require information on the hydraulic roughness, which is related to the type of land use. In the case of spatially varying hydraulic roughness values, the roughness may affect the flow pattern as the flow chooses that pathway with the steepest slope, but also with the minimal resistance. The hydraulic roughness also has an effect on the celerity of the flood wave and the computed water depths and flow velocities. Results from the pilot areas, however, show that the impact of uncertainties in the hydraulic roughness is much less than uncertainties in breach initiation and growth, wind or errors in the DEM. However, it should be noted that we have here only examined a limited number of sites and other studies have drawn subtle different conclusions.

4. Relevance to practice

The model results obtained for the pilot sites provide valuable information from which we have derived guidelines on model choice and model application (see previous section). These guidelines will be of help to anyone involved in inundation modelling for the implementation of the EU flood directive or for in any other field related to flood risk management (evacuation planning ,rescue of people, spatial planning in flood prone areas, etc.).

5. Remaining gaps in knowledge

Breaching

The assumption regarding breaching appears to be the key point in the study of the Scheldt pilot site, where the inundation is the consequence of a cascade of dike breaches. The most important parameters are the time of breach initiation (with respect to the peak time of the storm surge) and the breach growth rate. This implies that uncertainties in time of breach initiation and breach growth rates induce a high level of uncertainty in evaluating the time available for evacuation and rescue. Therefore, accurate breach growth models are required to simulate floods in tidal areas. A subject of further research would be to implement the breach growth models developed under **FLOOD*site*** Task 6 in the inundation models and use those for further sensitivity analysis.

More thorough benchmark

For a more thorough benchmark on inundation models, additional work should be undertaken on collecting better model validation data. The benchmark carried out in this study consists of a comparison of model results. As no accurate validation data are available, it is impossible to tell which model produces the most accurate results.

It could also be considered to use flume experiments for benchmark purposes, as this is the only way to eliminate uncertainties in for instance boundary conditions that may seriously affect the model results. For instance, a large data set exists for a flood along the River Eden in the UK, including the urban area of Carlisle. Aerial photographs of flood extent exist as well. However, as with all large floods there are questions over the accuracy of the discharge time series recorded at gauging stations during the event. An underestimation of the river discharge will result in an underestimation of the flood extent by the inundation models. This means that if the flood extent is used as a criterion to evaluate the models, the most accurate model will probably not be evaluated as such. Flume experiments have the advantage that the relevant data can be measured with a much higher accuracy.

A further way to overcome the problems of currently available field data sets would be to undertake a dedicated field monitoring programme during a future flood event using a combination of remote sensing and ground survey teams. This is logistically difficult, but ultimately may be the only way to address fundamental uncertainties concerning the fluid dynamics of real-world urban inundation

In the future we would like to carry out a benchmark together with the other research groups, such as the Flood Risk Management Research Consortium in the UK. This would enable a comparison of a much larger number of software packages.

Solid transport

Another important issue, not accounted for in most of the models is the solid transport associated to the flood flow. In some case, this transport may constitute a worse hazard than the water wave itself. In turn the solid transport may affect seriously the topography and worsen the flood in terms of water depth and local velocities. There exist some successful attempts to model this kind of phenomenon in simple situations like straight channels. Applicability to real-life situation requires heavy efforts of research.

Boundary conditions

From the additional sensitivity analysis reported in the final report of Task 8, it was concluded that uncertainties in boundary conditions can significantly affect the flood extent and water depths. In the Scheldt case, uncertainties in maximum water levels were in the order of 10 cm. However, differences in ebb water levels were much larger and appeared especially important in explaining the differences in simulated flood characteristics. This highlights the need for increased knowledge on water level time series over a longer period of time, instead of focussing on peak storm surge water levels only.

Other research questions

Other particular questions are still not completely solved and thus worth of further research efforts and developments:

- For one-dimensional approach:
  - more accurate estimation of interaction between main channel and floodplains
  - improved representation of distributed in- or outflow along rivers
  - improved modelling of bifurcations and confluences
  - optimal techniques for cross-section interpolation where required by the complexity of the river geometry
- For two-dimensional approach:
  - better definition of boundary conditions
  - development of porosity concepts for simplified urban areas representation
  - adapted turbulence models for shear stresses characterisation between cells
  - dealing with the computational limitations of storage cell models on fine grids
- For three-dimensional approach:
  - improvement of methods to determine water surface even in case of rapid variation in time and/or space

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