Two-Dimensional Modelling of Flood Hazards in Urban Areas

Case Studies: Reservoirs, Watersheds

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ABSTRACT

A comparison is made between a two-dimensional finite volume model and a TIN based approach using the results from flood simulations in urban areas. Maps from both models are presented showing flow depths, velocity, and flood intensities. Flood hazard maps are shown that have been created according to the new Swiss flood hazard policy. In the conclusions the results of the comparison are discussed and improvements for future applications are given.

1 Introduction

Flood hazard assessment is based on information on the intensity and the frequency of flood events. Usually the spatial distribution of both flow depth and flow velocity has to be considered. Assessing these parameters is difficult as the available information of past events is often sparse and of low quality. Numerical modelling could be a solution provided that the tools are accurate enough and easy to use.

Experience shows that one-dimensional (1-D) models that are appropriate for channel flows are difficult to apply for flows on flood plains as often:

- the flow paths are unknown and not possible to adequately describe in 1-D
- the flow paths change during a flood event
- backwater effects occur due to dams or dam-like structures

A further problem occurs when the results from the 1-D models have to be extended to two-dimensions according to geometric means [1]. For dry starts two-dimensional (2-D) models are more appropriate as the flow paths are automatically detected. This saves time setting up the model compared to 1-D models and makes the results more reliable. On the other hand 2-D models need more elevation data and in general they are more time consuming to run.

Therefore, a method has been evaluated that combines the advantage of 2-D modelling with the ease-of-use of 1-D models. This novel approach is presented together with a standard finite volume model which has already been used for various projects. Both models are applied to flooding problems in urban areas. The data is also presented in the form of hazard maps according to the new Swiss flood hazard policy that allows a discussion of the practical use of the models.

2 Swiss Flood Hazard Policy

2.1 Objective, Method, and Responsibility

The target of the Swiss flood hazard policy is to prevent urban development in hazard areas and to minimise interference with water courses [2]. Natural hazard processes are namely: flooding of water, erosion, and debris flow. The policy consists of the following steps:

(1) *Analysis:*What can happen where?
(2) *Assessment:*How often and with which intensity do hazard events occur?
(3) *Prevention:*Which measure can be applied for prevention?

The Federal Law on Flood Protection [3],[4] obliges the cantons (= regions) of Switzerland to assess the areas endangered by natural hazards. Hazard registers and hazard maps are used to depict these areas and deliver the information for land use planning measures.

2.2 Hazard Map

The hazard map consists of graphs and reports that define the spatial distribution of the hazard levels. The cantons are required to take the hazard maps into account for their guideline and utilisation planning. Therefore, the hazard maps are of prime importance for the whole assessment process and affect the land use and the planning of structural protection measures.

The hazard policy described in [5] distinguishes four different hazard levels each with a predefined colour and specific directions:

- **prohibited area**
  - no buildings allowed that host people or animals
  - no new objects allowed
- **area of orders**
  - construction allowed under restrictions
  - no sensitive objects should be build in this area
- **area of instructions**
  - information of owners about risks
  - measures for sensitive objects are necessary
- **area not endangered at current knowledge**

The hazard levels are functions of the probability and the intensity of hazard events according to the diagram in Figure 1. Additionally, events of *very low* probability have to be considered if sensitive objects are assessed. The flood prone areas are then coloured in white and yellow stripes.

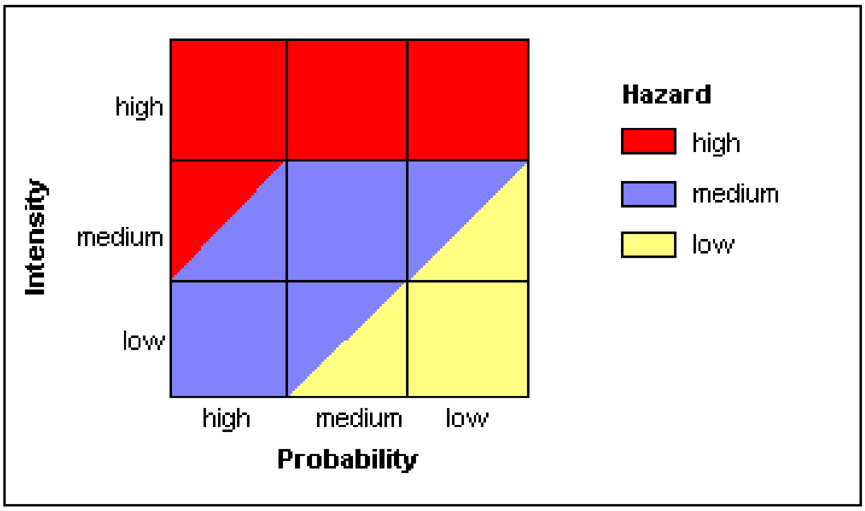


Figure 1: Diagram of hazard levels as a function of probability and intensity

The probability is a function of the return period of an event. The manual for flood hazard assessment [5] defines the probability as:

- *high* for a return period of 1 - 30 years
- *medium* for a return period of 30 - 100 years
- *low* for a return period of 100 - 300 years
- *very low* for a return period greater than 300 years

The flood intensity is a measure for the damaging effects of the flow. Flood intensities are defined in function of flow depths and flow velocities. For velocities smaller than 1 m/s the value of the flood intensity is equal to the flow depth. For higher velocities the intensity is defined as the product of flow depth and velocity (i.e. the specific flow). Therefore, the scales are either [L] or [L^2 T^{-1}]. The intensity is defined as:

- *low* for values between 0.0 and 0.5 [SI units]
  - persons are not endangered
  - limited damages of buildings are possible
- *medium* for values between 0.5 and 2.0
  - persons outside of buildings are endangered
  - no abrupt destructions, damages of buildings are possible
- *high* for values greater than 2.0
  - persons inside and outside of buildings are endangered
  - abrupt destructions of buildings are possible

Figure 1 shows that independent of the probability of an event areas with high intensities are considered as highly hazardous. For lower intensities the hazard levels depend on both intensity and probability.

2.3 Requirements for the Assessment Tools

Hazard maps have to be *reliable* and of *high quality* as they are the main output of the assessing process and form the basis of further planning measures. However, the means available for hazard assessment are limited. Models that are suitable must, therefore, be accurate enough and efficient to use.

The details of the flow field are not of prime importance for flood hazard assessment. Instead the simulation model must reproduce the important processes on a flood plain which are namely: breakouts from rivers, overtopping of dams, flows from the flood plain back into a river channel, backwater effects, retention behind dams, effects of culverts and obstructions. The accuracy of the model output must allow to distinguish between the four different intensity levels defined above. Thus it might be sufficient to estimate the flow depth with an accuracy of 0.2 - 0.5 meters. On the other hand, creating hazard maps from intensity values requires the simulation of many different scenarios. Ideally a typical computation would not last more than a few minutes and would allow for a quick analysis of the results. - Having defined the requirements for the assessment tools two different models are presented that could be used for flood plain modelling.

3 Finite Volume Model

The first model is based on a standard finite volume (FV) approach to solve the depth-averaged shallow-water equations. The equations describe the conservation of mass and momentum and can be written in Cartesian co-ordinates as

$$\begin{aligned}
&\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} + \frac{\partial r}{\partial y} = 0 \\
&\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{h} + g\frac{h^2}{2}\right) + \frac{\partial}{\partial y}\left(\frac{qr}{h} - h\frac{\tau_{xy}}{\rho}\right) + gh\frac{\partial z}{\partial x} + \frac{\tau_{bx}}{\rho} = 0 \\
&\frac{\partial r}{\partial t} + \frac{\partial}{\partial x}\left(\frac{qr}{h} - h\frac{\tau_{xy}}{\rho}\right) + \frac{\partial}{\partial y}\left(\frac{r^2}{h} + g\frac{h^2}{2}\right) + gh\frac{\partial z}{\partial y} + \frac{\tau_{by}}{\rho} = 0
\end{aligned} \tag{1}$$

where t = time; x,y = co-ordinates in horizontal plane; h = flow depth; q,r = components of specific flow; g = gravitational acceleration; z = bed level; t_{xy} = turbulent shear stress; $t_{bx,y}$= bed shear. Turbulent stresses are estimated using a zero-equation model (shear stress) or are neglected (normal stress). Bed friction is expressed by Manning's formula.

Stability for sub- and supercritical flows is accomplished using a cell-centred variable location. The numerical fluxes are evaluated according to Roe's difference splitting method and variable extrapolation or MUSCL approach with a symmetric limiter [6]. The solution is sought with an explicit two-step predictor-corrector scheme on a uniform rectangular grid. More details about the model can be found in [7].

The FV scheme has been implemented in the code Hydro2de. The program has been widely used for various flow conditions, including braided river flow [8], flows in mountain streams [9], and flows on flood plains [10]. Applications with up to 400.000 cells have been performed which was practicable due to the numerical stability of the model under difficult flow conditions (i.e. high gradients of bed elevations, transcritical flow regimes). The model can handle dry starts and thus is suitable to simulate flows on initially dry flood plains.

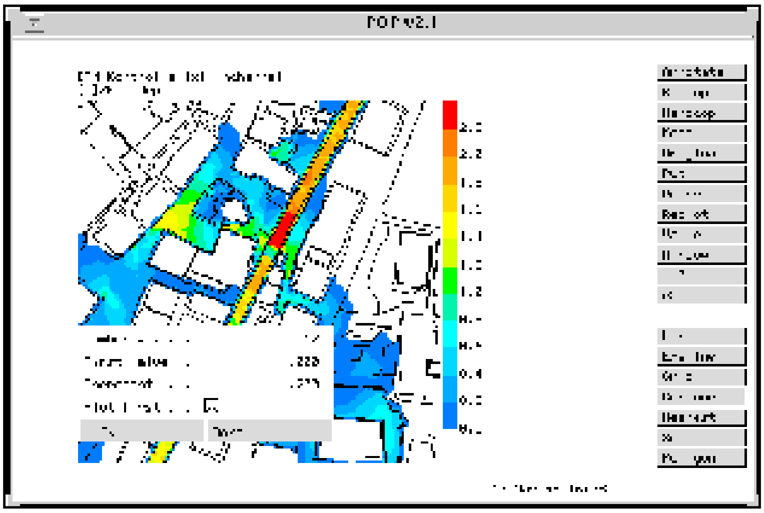


Figure 2: Analysing results from the FV model Hydro2de

4 Partial Discharge Model

Triangulated irregular networks (TINs) represent an efficient method to describe ground surfaces and dam-like structures (e.g. motorways, railways) in a digital terrain model (DTM). Ideally the flow equations would be solved directly on the TIN data, but existing numerical methods (finite volumes and finite elements) require smoother grids to converge and to maintain the accuracy. It has been found that flows on flood plains and braided flows are driven mainly by the slope of the water level and thus the numerical accuracy of these models is not crucial [8]. Instead it is important to avoid errors resulting from the representation of the ground surface.

Therefore, a modelling concept has been investigated that directly applies to the TIN representation of the surface elevation. It is based on a reduced flow equation obtained from the momentum equation in Eq.(1) written as

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{h} + g\frac{h^2}{2}\right) + gh\frac{\partial z}{\partial x} + \frac{\tau_b}{\rho} = 0 \tag{2}$$

where q = specific flow along the cell edge; t = time; x = distance along the cell edge in horizontal plane; h = flow depth; g = gravitational acceleration; z = bed level; t_b = bed shear.

The equation contains the terms for the static and dynamic forces, the slope of the bed level, and the losses due to bed friction. It does not account for the momentum flux due to perpendicular flows and for the turbulent stresses. Eq.(2) is solved along the edges of the TIN using a novel approach named Partial Discharge (PaD) method. For this reason the input flow given as an internal source is divided into parcels of water (PaD elements) that are distributed using a random walk approach (see Figure 3).

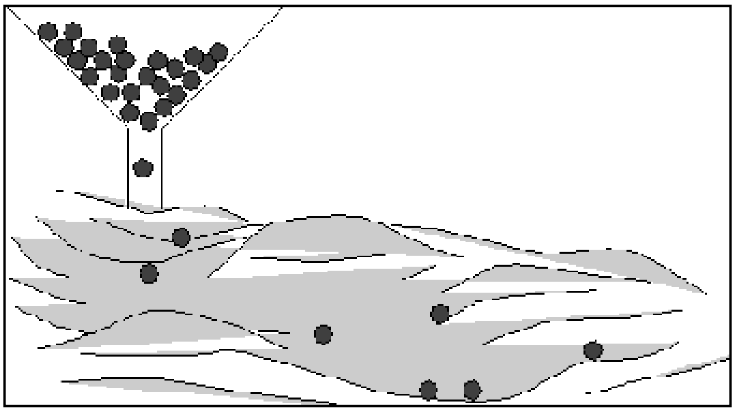


Figure 3: The PaD concept: Parcels of water moving along gradients of the surface elevation

The procedure acts on each parcel of water starting from the node at the location of the input source. The flow chart in Figure 4 shows the different steps and loops that have to be worked out for the final solution. The PaD method can be used for steady and unsteady flows. For steady flows the volume check in the lower loop of Figure 4 is omitted.

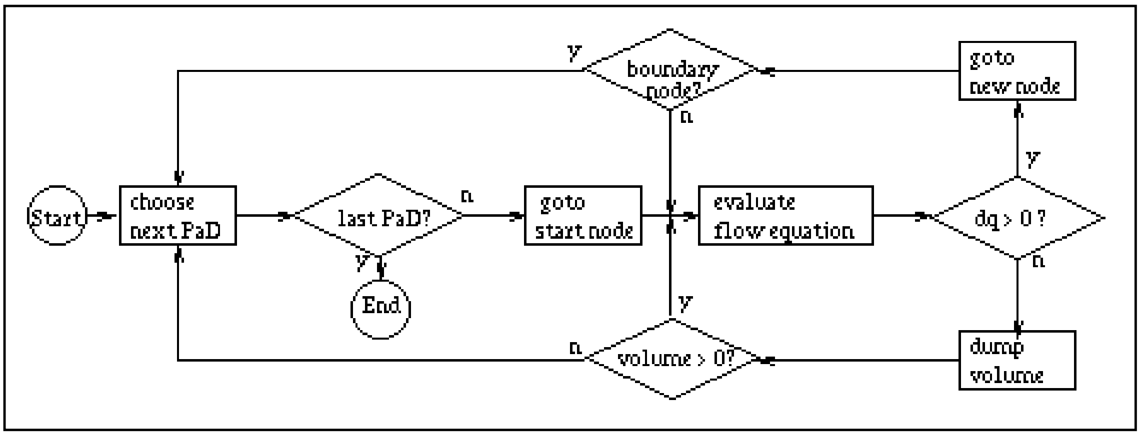
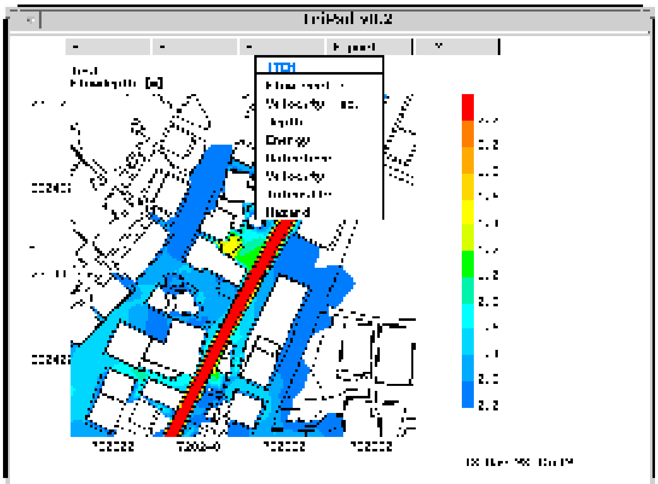


Figure 4: Flow chart of the PaD procedure

The PaD approach allows simulation of the flooding from local sources and accounts for flood retention due to storage in depressions and behind dams. It is suitable to model the flooding due to overtopping of dams or the flooding caused by obstructions of culverts and bridges. Inputs of the model are: the location of one or several flood sources, the discharge of each source, and for unsteady flows the total water volume. - A limitation for unsteady flows is that the model does not account for the emptying of flooded areas. If the water is dumped once it is assumed that it remains there for the rest of the flood event. Underestimation of flow depths can be avoided by increasing the total volume of the discharge.



The PaD method is stable independent of the geometry of the grid which is important when applied to the original data of the TIN. The method has been applied to the steady one-dimensional channel flow equations where it converges to the standard backwater solution except that hydraulic jumps are not correctly located [11]. For two-dimensional flows the method has been included in the computer program TriPad. The code is menu driven and allows for graphical in- and output of the results. The version used in this paper neglects the effect of the dynamic forces. Future versions will also account for this term.

Figure 5: Program TriPad

5 Applications

Two application are presented that have been investigated as part of a pilot project for the Board of Natural Hazards of the canton of St. Gallen. The first application demonstrates the use of the models for detailed flow modelling in urban areas. The second application shows a larger area with flow over open farmland.

5.1 Flow through a Township

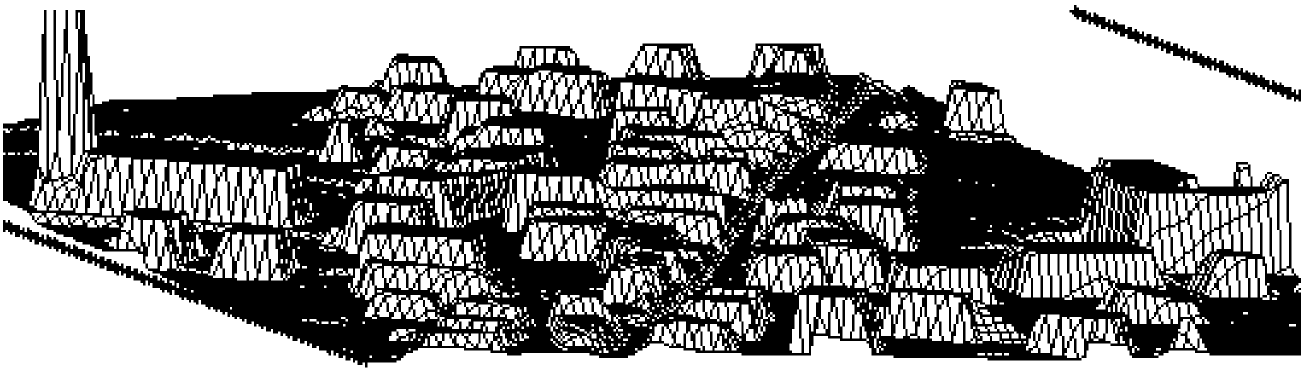


Figure 6: Perspective plot of the DTM

The modelled domain covers an area of 200x400 meters and represents a township located on a alluvial fan with a mean surface slope of 4%. Figure 6 shows a perspective plot of the town including the church and tower (left side) and the river channel (from upper right to lower left corner) with a width of 5 meters. The ground surface has been surveyed by aerial photogrammetry. Roads, river channel, and buildings are described with breaklines, and additional terrain points have been added to improve the meshing. The TIN of the ground elevation has been created with Delauney triangulation. From this the uniform mesh for the FV model has been generated by linear interpolation. The grid spacing chosen was 1x1 meter as coarser grids did not correctly modelled the flow in the river channel.

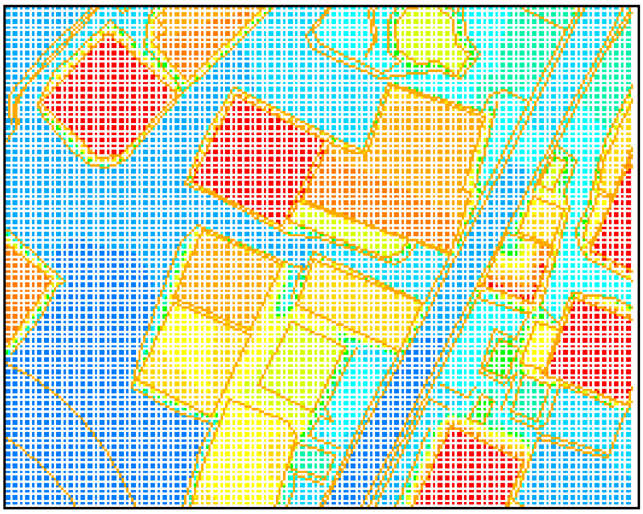


Figure 7a: Surface elevation with 1x1 meter FV grid (detail)

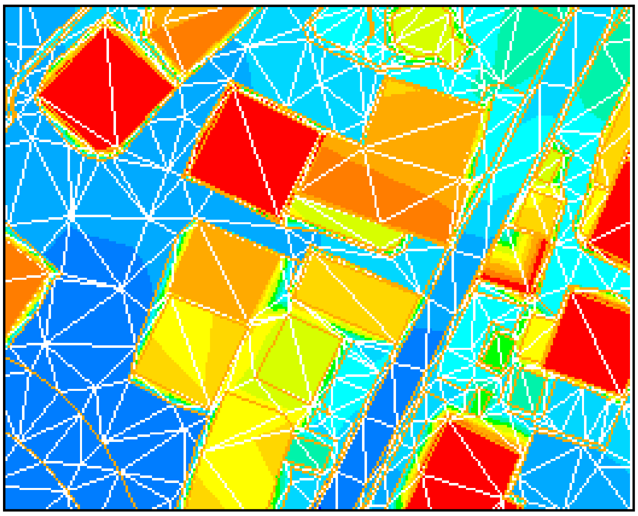


Figure 7b: Surface elevation with TIN (detail)

The township gets flooded for discharges that exceed the capacity of the river channel or due to obstructions at the bridge sections. Hydraulically spoken the roads act as flow channels and thus the location and dimensions of the buildings are important. Sub- and supercritical flows are likely to occur as the slope of the terrain exceeds 0.5%.

Both, the FV and the PaD model has been applied to calculate the flow field starting from a dry domain. For the boundaries of the models critical flow has been assumed (i.e. no backwater effects occur). Typical run times were 180' for the FV model and less than 1' for the PaD model on a Pentium 300 MHz processor. The long computation times with the FV model are mainly due to the fine gridding.

In Figure 8 the predicted flow depths are shown for a scenario when the channel is locally filled up (red circle in Figure 8a). As a consequence the water leaves the channel and distributes along the roads and paths between the buildings. Below the obstruction portions of the flow also returns back into the channel. It can be seen that the main paths of the flow are well reproduced with both models. Differences show up for the narrow flow paths and the distribution of the flow. The FV model predicts slightly higher discharges to the left side than the PaD model, and vice versa.

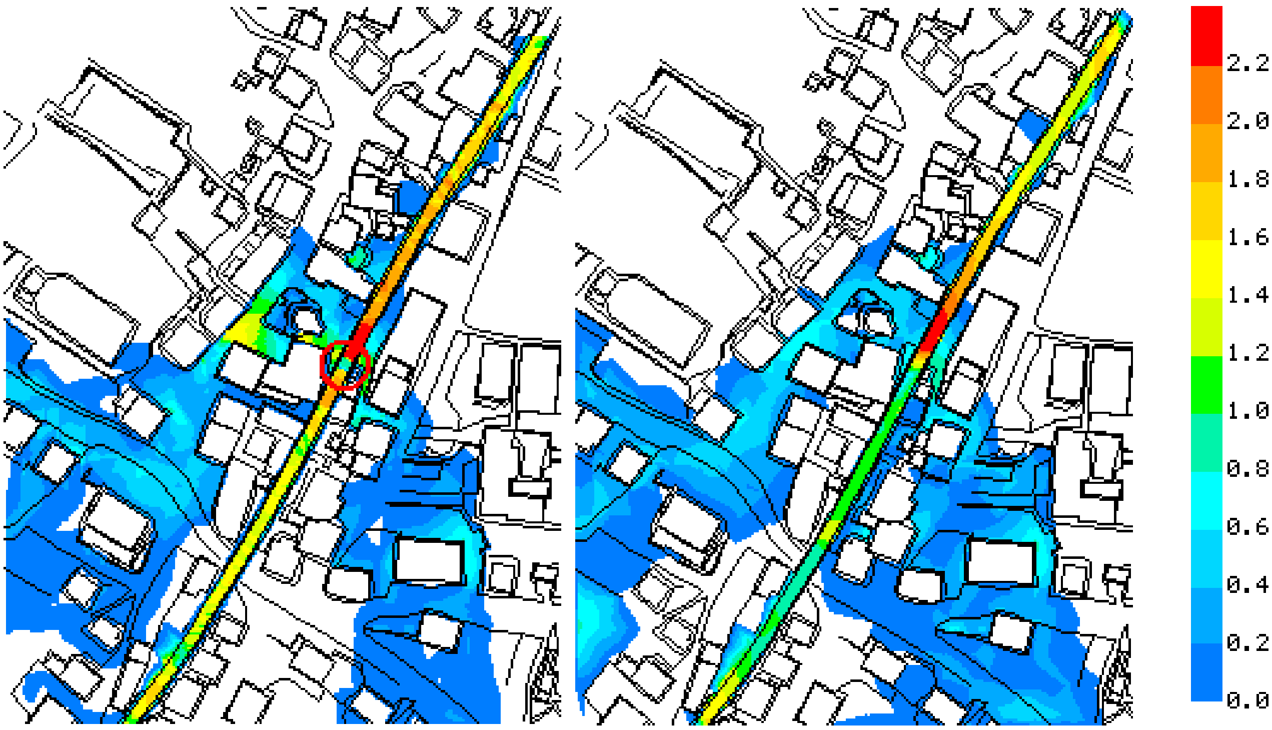


Figure 8a: Flow depth [m] with FV model

Figure 8b: Flow depth [m] with PaD model

As the FV model solves the full momentum equation it gives more accurate results for the flow field, e.g. the influence of eddies and separations (Figure 9a). However, the estimated flow depths show that the uniform grid is not ideal to model flows in narrow river channels. This problem is further addressed in [10].
- The PaD model gives more accurate results for the channel. The edges of the TIN coincide with the direction of the flow as breaklines have been used to describe the geometry of the channel. Eddies and separations are not reproduced with the PaD model (Figure 9b). Accordingly the PaD model underestimates the flow depths at contractions and abrupt expansions.

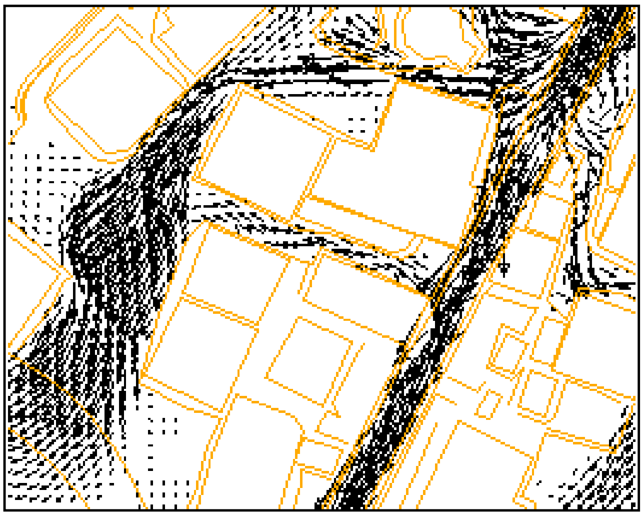


Figure 9a: Velocity vectors with FV model (detail)

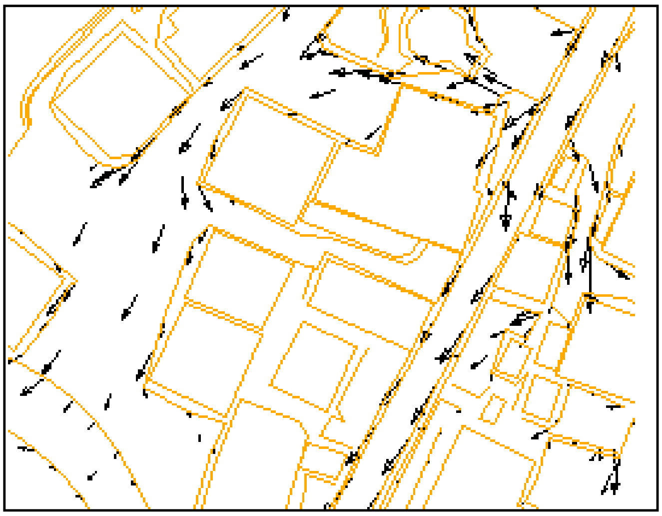


Figure 9b: Velocity vectors with PaD model (detail)

5.2 Flow on an Alluvial Fan with Flood Plains

The modelled domain covers an area of 1200x1400 meters of a settlement on an alluvial fan and the flood plain south of the railway line that divides the area from west to east. The surface slope varies from 2.5% on the fan to 0.4% on the flood plain. The area has been surveyed by aerial photogrammetry and evaluated by 30.000 terrain points (including breaklines). A creek of 4 meters width flows on top of the fan and can overtop the dams for high discharges. It passes the railway embankment through a culvert that is assumed to get obstructed for events with a return period higher than 30 years.

A simultaneous modelling of the creek and the flood plain was not practicable with the FV model as the computation times would have been too long (approx. 9 days for a grid of 1x1 meter). Thus it was decided to use a relative coarse grid (6x6 meters) for the FV model and calculate the creek separate with a standard backwater code. The cross-sections for the 1-D model were estimated directly from the DTM data. The breakouts from the river were then used as internal sources for the FV model starting from a dry domain.

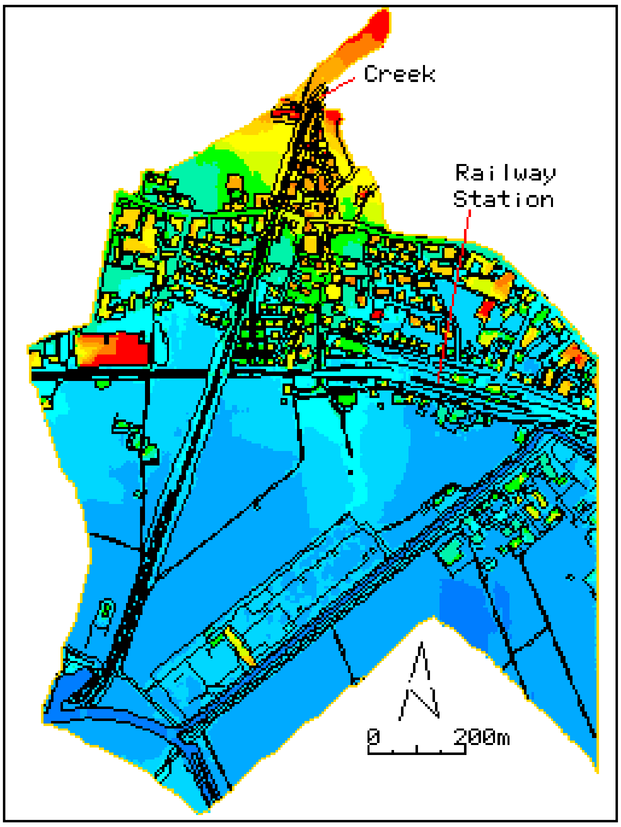
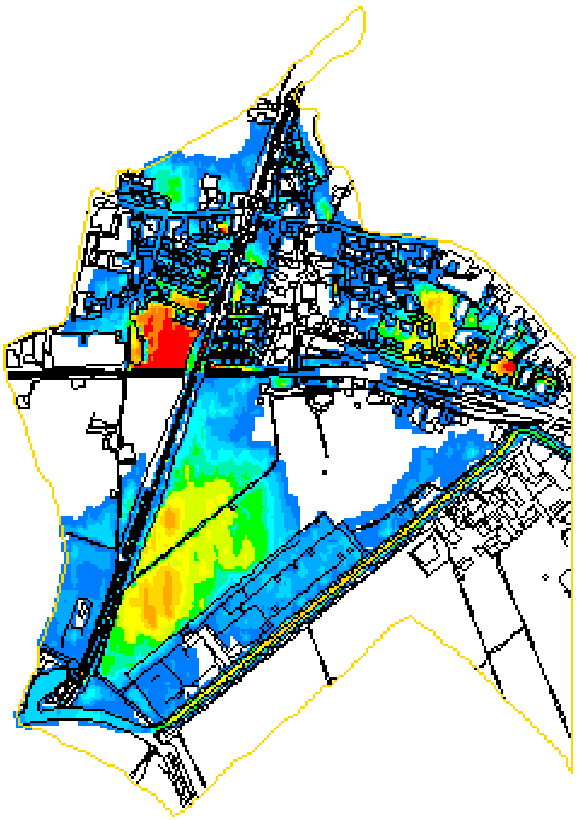


Figure 10: Surface elevation of the domain

The PaD model, on the other hand, could be applied directly to the TIN data. A separate calculation of the creek was not necessary which saved time and avoided errors from decoupling the 1-D and 2-D models. In both models a constant Manning's n value has been used for the whole domain (n=0.033) and at the boundaries a critical flow condition was assumed. As these assumptions do not hold in reality the results do not show up the actual hazard situation of the modelled area.



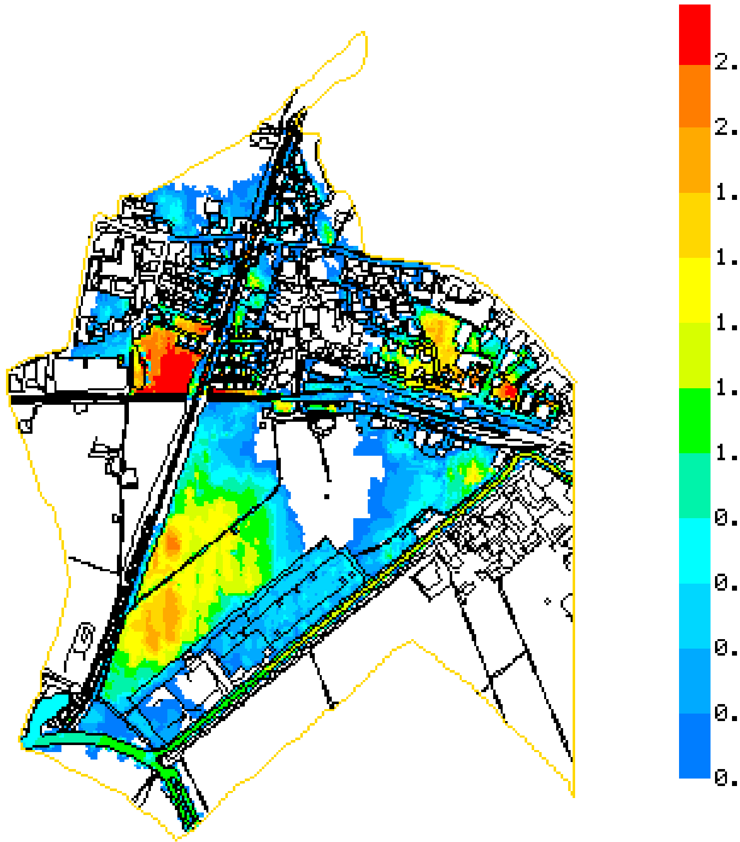


Figure 11a: Flow depth [m] for HQ100 with FV model Figure 11b: Flow depth [m] for HQ100 with PaD model

The computation times were 90' for the FV model and approx. 2' for the PaD model. A close agreement between the predicted flow depths for the 100 year flood can be seen in Figure 11a and 11b. The backwater effects behind the railway embankment are correctly reproduced by both models. Also the flow depth on the flood plain and in the township compare well. Differences can be found in the area south/west of the channel. With the FV model the area gets flooded as the coarse FV grid does not correctly describe the levee along the channel. Corrections would have been necessary here. On the other hand the PaD model predicts a flooding of the area south/east of the railway embankment as the narrow flow paths between the buildings are better represented than with the uniform FV grid.

Information of past events is of high value to complement the results from the modelling. The following observations have been found in a local newspaper:
(1) During the flood event in 1934 (= largest flood of the century) the observed flow depths in the township reached 1.0 to 1.5 meters . . .
(2) In 1977 an outbreak from the river channel at the top of the domain could only be prevented with emergency measures . . .
Comparison with the predicted flow depths shows that these historical statements correspond well with the findings of the numerical models and support the results.

From the practical point of view it is also important to know how much the results differ when the models are used to predict hazard levels. Figure 12 shows the hazard maps created from intensity values. It can be seen that the same remarks are valid for the hazard map as for the spatial distribution of the flow depth. The two models give equal hazard levels in most areas. Differences can be found where the relative coarse grid of the FV model suppresses the effects of narrow terrain structures. There is no indication that errors occurred due to the simplifications in the PaD model.

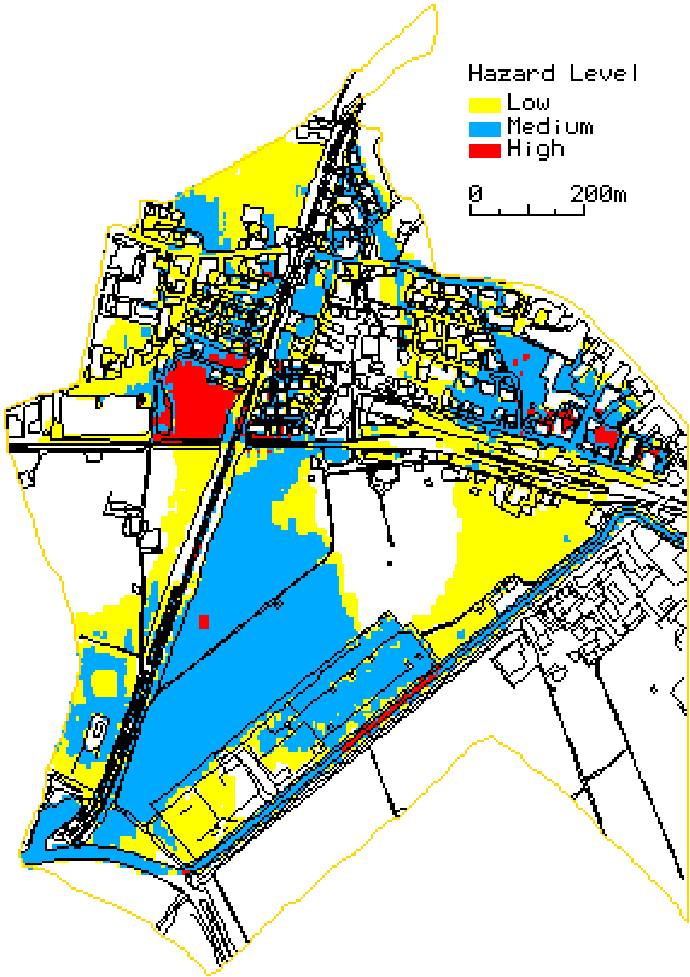


Figure 12a: Hazard map with FV model

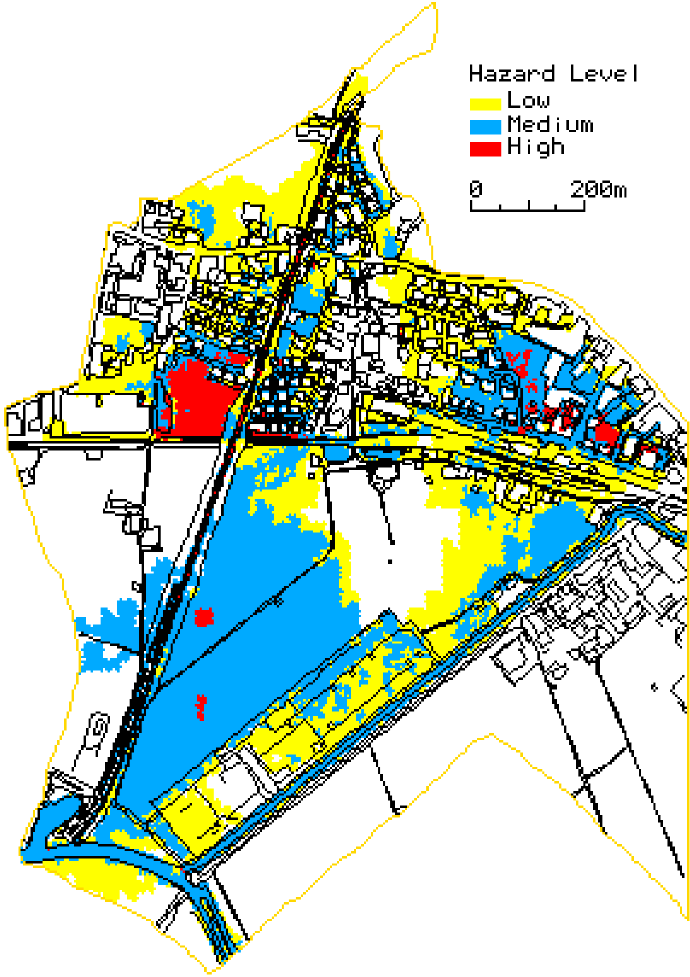


Figure 12b: Hazard map with PaD model

The hazard maps shown above have been created from intensity maps from the 30, 100, and 300 year floods shown in Figure 13a for the FV model and in Figure 13b for the PaD model. The differences between the models are more significant for the 30 year flood since errors in the surface elevation have a greater effect for smaller floods when overtopping of dams occurs locally than for large floods with broad overtopping. - Presenting a sequence of intensity maps can be used to analyse the sensitivity of the results for changes in the boundary conditions. There are areas in the flood plain that have almost the same intensity levels for all three floods. The township, on the other hand, is only affected for higher floods. The interested reader will also note that the PaD model predicts partial flooding of the area south/west from the creek for the 30 year flood but no flooding for the bigger floods. This is not an error of the model but is due to the assumptions made for the culvert flow (open for the 30 year flood and obstructed for greater floods). It is clear that the floods should be modelled twice (with and without obstruction of the culvert). This would take only 4' with the PaD model or another 3 hours with the FV model!

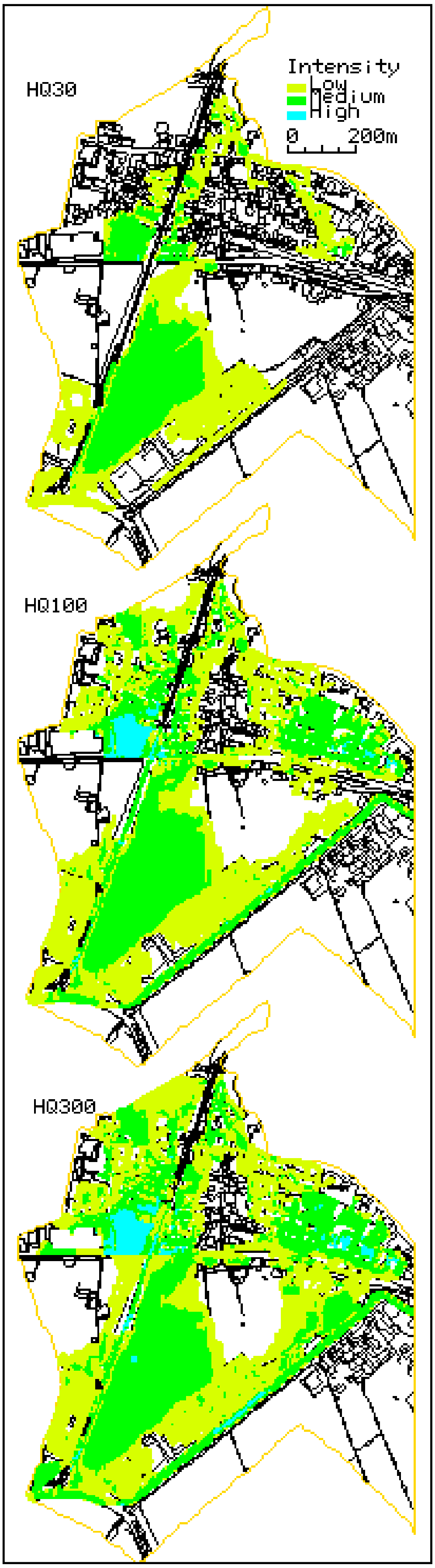


Figure 13a: Flood intensities with FV model

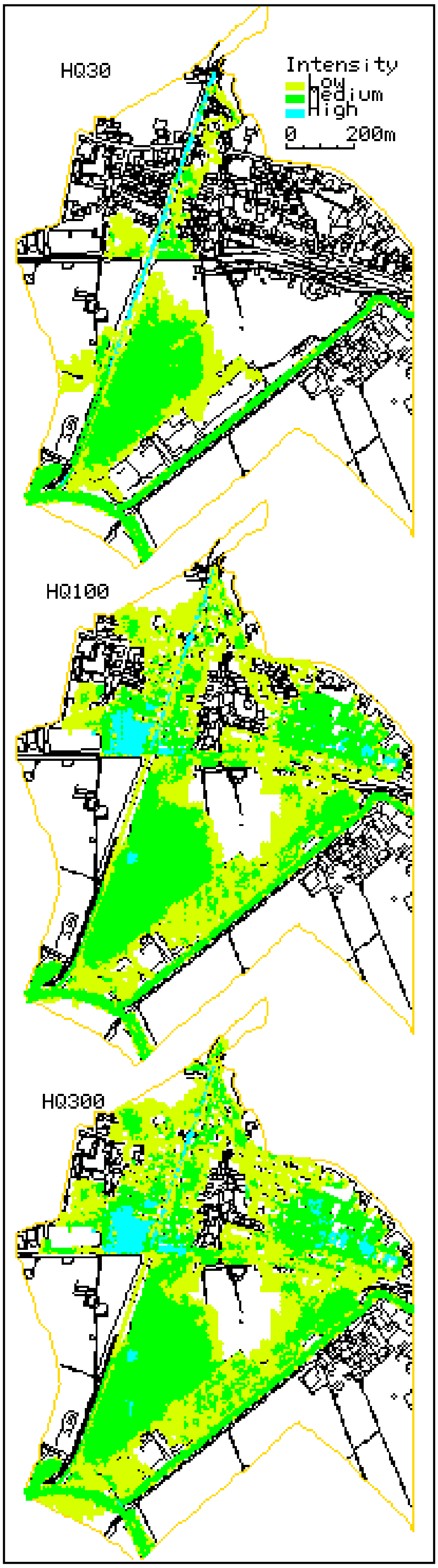


Figure 13b: Flood intensities with PaD model

6 Conclusions

Two models have been applied for flood simulations in urban areas: a finite volume model based on a uniform grid, and a new approach that directly applies to the TIN data (PaD model). Both models are found suitable to reproduce the flooding of initially dry areas with moderate and high slopes. The comparison of the results shows a good agreement between the two models for the flows on flood plains. Differences can be found for narrow channels and flow paths between buildings. These differences are mainly due to the coarseness of the uniform FV grid for narrow channels and the PaD model not allowing for the side effects which become significant at contractions.

The FV model solves the complete shallow-water equation and thus can reproduce the details of the flow structure provided the calculation mesh is fine enough. For larger areas the calculation time becomes a limiting factor. Thus it is not practicable to model fine terrain structures (e.g. narrow channels) for large areas. In this case a separate calculation with a 1-D model would be necessary which makes the application more complicated.

The PaD model is based on a simplified flow equation and thus can not reproduce the details of the flow structure (e.g. eddies, separations). Compared to other numerical schemes it has the advantage that it directly applies to the TIN of the ground surface. Thus it exempts from creating an additional calculation mesh which saves time and avoids errors from interpolation. The calculation time is very modest which allows to calculate large areas with many different scenarios. This is important for applications where obstructions or similar processes increase the number of scenarios for the assessment.

The applications show that the PaD approach offers exciting new possibilities for flood plain modelling. However there still exist some open questions about the limitations of the PaD method, e.g. how the results depend on the geometry of the TIN. As the numerical fluxes follow along the edges of the grid, the TIN has to correctly represent the possible flow paths, or more terse: no edge - no flow. Experience shows that errors might occur but they are reasonably small if the geometry of the TIN observes minimum rules. Future research will address this point and highlight the already known limitations of the PaD method. This will help to further improve the quality and the reliability of the results for flood hazard assessment.

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