TRENDS IN THE NUMERICAL MODELLING OF FLOODS

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Introduction

In Europe, significant budgets are made available to reduce the worst effects of floods. As a result, flood simulation and forecasting techniques have been developed at a high professional level. One of the worst recent floods occurred in the Czech Republic and in Germany in 2002. The events had return periods of once in 500 years in Prague and once in 200 years in Dresden, respectively. The resulting flood damage has been estimated at more than € 2.3 billion in the Czech Republic and € 9.2 billion in Germany. More than 130 river dike breaches occurred in the German federal state of Saxony alone.

In The Netherlands, the 1953 coastal floods had enormous impacts in terms of loss of life and subsequently in terms of flood protection measures taken. More recently, the river dikes were threatened during the floods in 1993 and 1995. In this last year, 250,000 people had to be evacuated from the Tieler and Culemburger Waard. The economic damage could have been € 18 billion if the dike would not have been saved during emergency operations.

In particular these flood threats in The Netherlands have led to the following important developments:

- Systematic analysis of the risk of flooding of dike ring areas;
- Delft flood forecasting platform – Delft-FEWS;
- Delft 2D/3D generic modelling system – Delft-3D;
- Delft 0D/1D/2D generic modelling system – SOBEK;
- Integrated approach to modelling.

In this paper we will focus on a new approach to flood risk analysis and the role that numerical flood models play as part of this. Examples of early work on the development of numerical models for flood simulations are given by Dronkers (1969).

A New Approach to Flood Risk Analysis

Figure 1 shows the map of The Netherlands with the level of protection offered for various areas (so-called dike ring areas; areas enclosed by levees or natural high grounds), depending on risk of life and economic importance. Decisions on these safety levels were made after the 1953 floods and defined on the basis of water level frequencies along the various dike sections. After the flood threats of 1993 and 1995it was realised that the risk of flooding had to be evaluated on the basis of a systematic analysis of all possible causes of floods and not only the probability of exceedance of embankment levels. Other important failure mechanisms are piping, failure of hydraulic structures, neglected maintenance etc. After all: “a chain is as strong as its weakest link”. A new methodology was developed for the analysis of the safety of 53 dike ring areas with their 3500 km of primary dikes in The Netherlands.

An important tool in the analysis has been the use of integrated 1-dimensional – 2-dimensional hydrodynamic models, based upon a detailed description of the topography of the dike ring areas and a wide variety of failure mechanisms.

In this paper we will limit ourselves further to a description of recent developments in the area of numerical flood simulation.

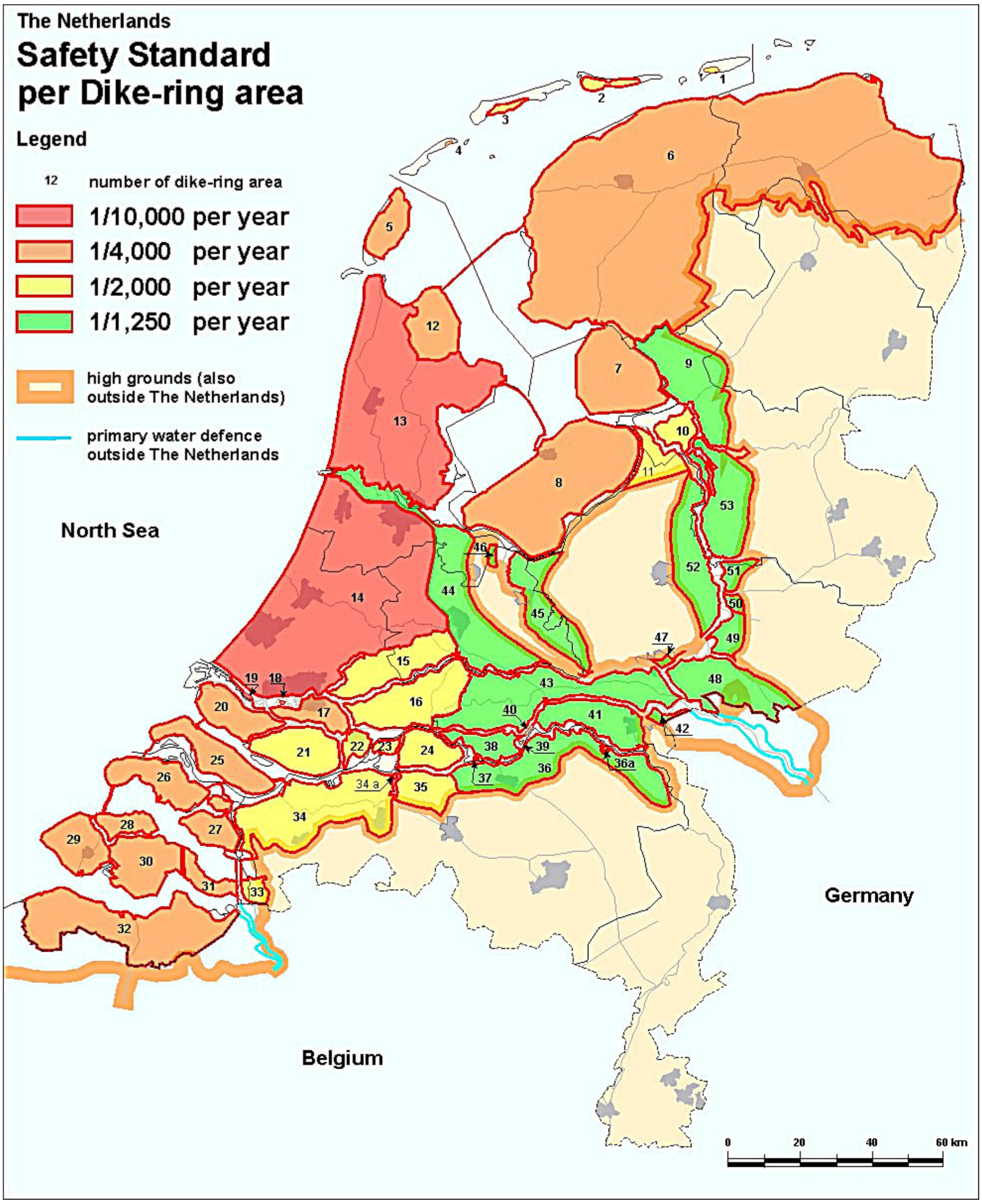

Figure1 Dike-ring areas in The Netherlands classified according to flood protection level (courtesy: Department DWW of the Directorate General for Public Works and Water Management in The Netherlands)

Flood Modelling Developments

Over the past decade there have been significant developments in the area of numerical modelling to support flood management and flood forecasting operations. The following issues will be discussed briefly:

- Developments in data collection;
- Developments in data processing;

- Developments in computer technology;
- Developments in numerical methods;
- Developments in model integration.

Data Collection

For flood forecasting systems the choice between hydrological and hydraulic routing models have led to many discussions based upon data needs. Hydrological routing methods are developed on the basis of measured flood hydrographs, whereas hydraulic models primarily use topographic information for their development and use the flood hydrographs as additional information for model calibration. Over the past decade the LiDAR technology has been developed. With this technology the surface of the earth is scanned with laser beams from air planes or helicopters, enabling vast sets of terrain level data to be collected efficiently (e.g. Verwey, 2001, 2006; Franken and Flos, 2005). In this last paper the state of the art of LiDAR technology is described as applied to dike inspection.

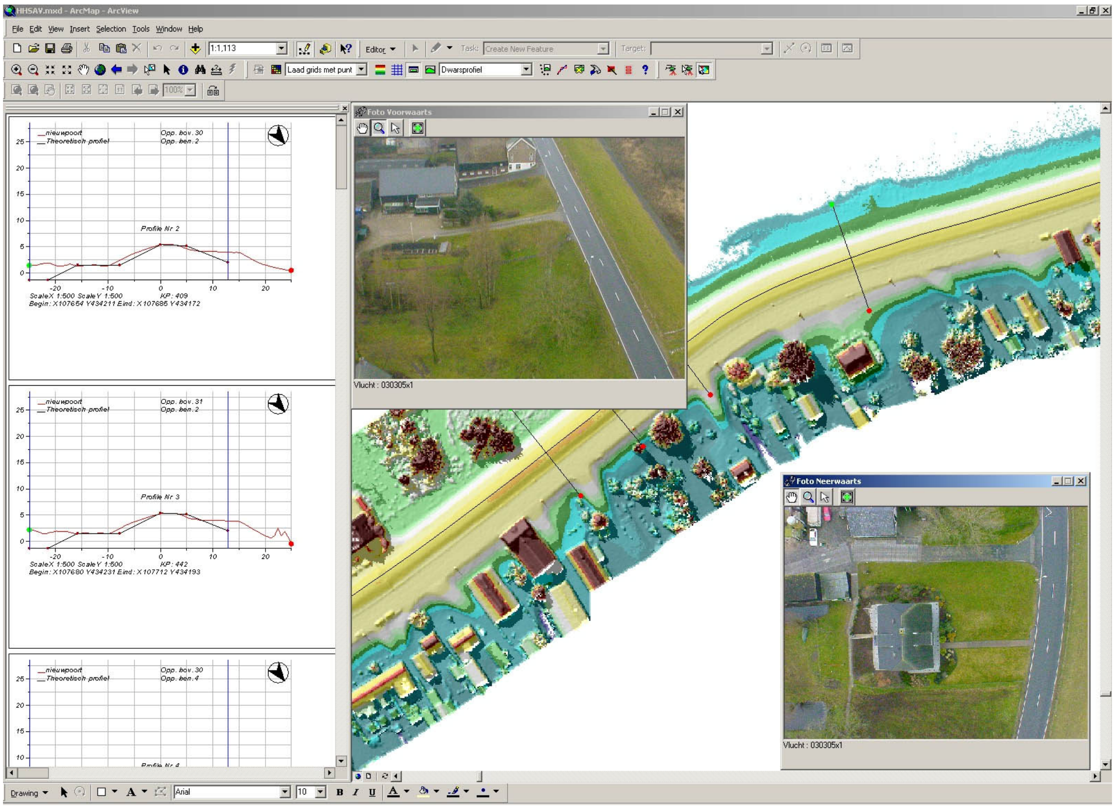

Figure 2 Integrated LiDAR image viewer for dike inspection (courtesy Fugro, TheNetherlands)

In particular in The Netherlands, the need for 5-yearly inspection of embankments, recognized and institutionalized after the 1993, 1995 river floods, has given a further push to the development of LiDAR technologies, to acquire data of a uniform quality and at high speed. Partly for this purpose, the multinational engineering company Fugro (www-fugro-inpark.nl) has developed its FLI-MAP® (Fast Laser Imaging and Mapping Airborne Platform) system. It operates at altitudes of 50-400 m and delivers maps at a 10-100 point density per m2, recently extended to a 400 point per m2density. The quality of data collection has been enhanced by applying 4 integrated photo and video cameras and a double laser system to eliminate shadowing. The system enables the inspection of 100-150 km of line element per day. Quality of data collected is at a systematic error of 5 cm and a standard deviation of 5 cm in X and Y and at 5 cm and 3 cm, respectively, in Z. With the aid of specially designed software in ArcGIS, measured (actual) profiles can easily be compared with the designed (theoretical) ones (Fig. 2). In this way it is easy to check longitudinal and crossprofiles on soil subsidence effects and transversal profiles on possible stability problems.

Similar developments take place in cross-section surveying, which is now supported by the multibeam echo sounding technology and DGPS. So the picture has changed and the use of hydrodynamic models is becoming more and more state of the art, usually fully justified by the economic importance of studies. Models based upon digital topographic data behave better under extrapolated conditions. This is a particular advantage for flood management and flood forecasting applications, when dealing with extreme events. The availability of digital topographic data also favours the use of 2D simulation models, which can be set up without the schematization errors that come in when 1D models are used for the simulation of flow over complex terrains. This is often the case with wide flood plains, such as the Plain of Reeds in Vietnam and Cambodia and in urban areas.

Data Processing

There is no need to elaborate in detail on the data processing facilities. Over the past decade, many authorities dealing with water have invested significantly in good data management, including quality control. This also applies to the Mekong Basin. GIS is commonly in use now to feed models with physically based parameters. An example is land use maps, which serve to estimate terrain roughness parameters. This has also led to further research on the relation between vegetation height and roughness parameters (Baptist et al., 2006). GIS also serves in a routine way the presentation of numerical model results. Current post-processing activities based upon model simulations lead to damage assessment, web-based flood or other environmental warnings, etc.

Computer Technology

In computer technology still Moore’s law applies since it was stated in 1965 that the density of transistors on a chip doubles every 2 years. Currently, the precision in chip production is 65 nm (2005). Computer experts are convinced that the precision will increase to 10 nm in 2015, which will guarantee the validity of Moore’s law at least until that time. This implies that both storage capacity and computation speed will continue to double every two years. This means that operations currently taking 1 hour, will be executed in one minute only, 12 years from now. Commercial drive currently is the media world and the water sector continues to profit from this.

Numerical Flood Simulation

Numerical methods for flood simulation have matured these days. Of particular interest in flood simulation is the current robust behaviour of flooding and drying of computational cells. The robust description of the full convective momentum term in the momentum equation(s) allows for the correct simulation of transitions between sub- and super critical flows vice versa. Examples of such numerical improvements have been given by Stelling and Duinmeijer (2003) and Stelling and Verwey (2005). Dam- or dike breach simulations, in particular, have been demanding above improvements. Currently, also robust, numerically implicit methods have been developed for the coupling of 1D and 2D computational domains. Such coupled models also need the efficiency improvements in solving implicit numerical schemes. A high efficiency has been achieved by using optimum combinations of direct matrix solvers and the conjugate gradient technique within one integrated model.

All such developments, jointly with the better access to data via internet allow us to quickly set up pilot models. As an example, the flood simulation model for the City of New Orleans (Fig. 3) was constructed during the week the Katrina event took place, by downloading the digital elevation model available on the USGS web site and collecting additional information from a variety of places on the web. Such models are very useful as a hind cast tool in order to explain consistently what happened. This in turn will form the basis for discussion on how to proceed toward a more sustainable situation. It should be realised, though, that more precise models still need more development time than the few days required for the pilot model.

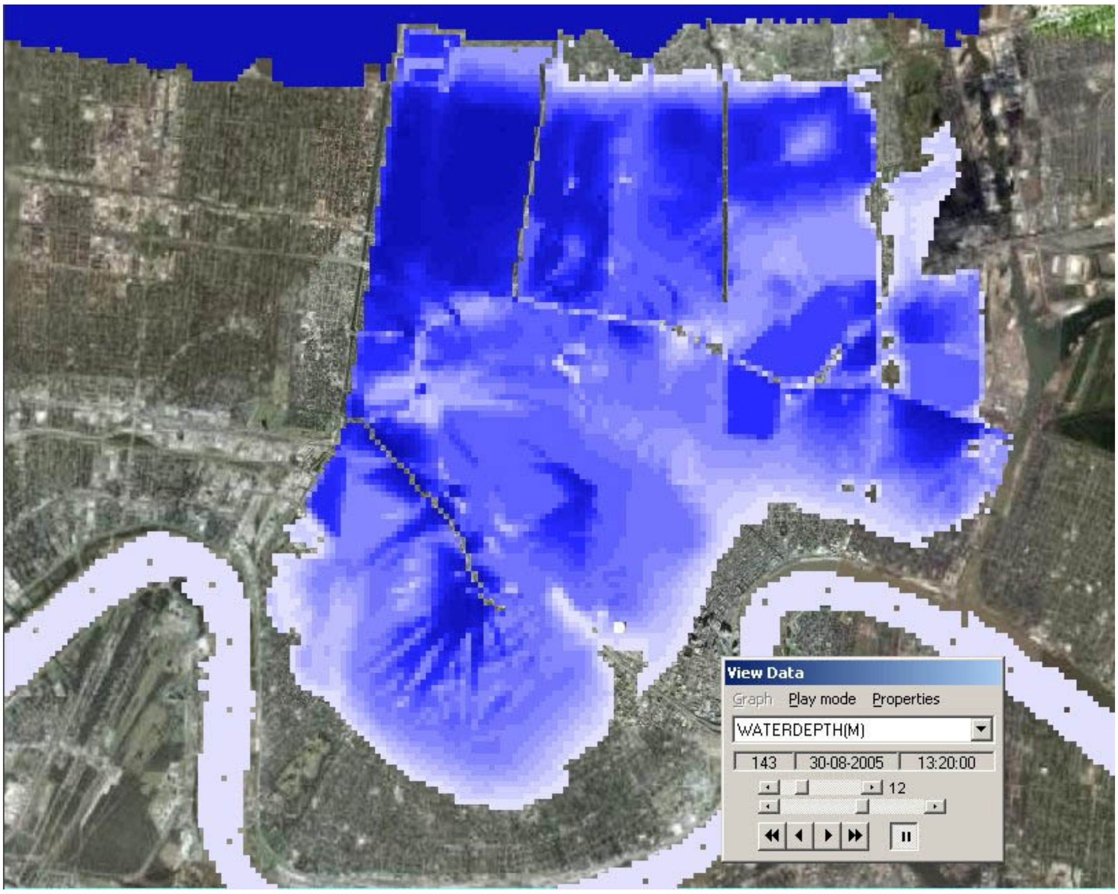

Figure 3Simulation with SOBEK 1D/2D of the flooding of the City of New Orleans resulting from the Katrina hurricane.

Model Integration

Above developments have a significant impact on the way we schematize and develop flood simulation models. For example, an obvious trend is to move from pure 1D or2D models to integrated 1D-2D models. There are numerous situations where flows are best described by combinations of 1D and 2D schematizations.

An obvious example is the flooding of deltaic areas, such as the Mekong Delta, characterized by a flat topography with complex networks of tidal rivers, drainage channels, natural levees, polder dikes, elevated roads and railways and a large variety of hydraulic structures. Flow over the terrain is best described by the 2D equations, whereas channel flow and the role of hydraulic structures are best described in 1D.Flow over higher elevated line elements, such as roads and embankments can be modelled reasonably well in 2D by raising the bottom of computational cells to embankment level. However, for a higher accuracy of the numerical description adapted formulations have to be applied, such as energy conservation upstream of overtopped embankments.

Another example is the flood propagation in a meandering river, with shortcuts via the flood plain when over bank flow occurs. In large scale models, the flow between the river banks is satisfactorily described by the de Saint Venant equations solved with 1D grid steps several times the width of the channel. An equivalent accuracy of description in 2D would require a large number of grid cells, with step sizes being a fraction of the channel width. However, flow in the flood plain may be better described in 2D and may allow for 2D grid steps often exceeding the width of the river.

For these reasons, hybrid 1D and 2D schematizations are more and more applied. Basically there are two approaches: one with interfaces defined between 1D and 2Dalong vertical planes and the other approach with schematization interfaces in almost horizontal planes.

Coupling along vertical planes, gives in the horizontal space a full separation of the domains modelled in 1D and 2D. In the 1D domain the flow is modelled with the de Saint Venant equations applied over the full water depth. The direction of flow in the1D domain is assumed to follow the channel x-axis and in the model it carries its momentum in this direction, also above bank level. Without special provisions, there is no momentum transfer accounting applied between the 1D and 2D domains. Momentum and volume entering or leaving the 2D domain at these interfaces are generated by the compatibility condition applied. As a result, the coupling cannot be expected to be momentum conservative. Depending on the numerical solution applied, the linkage may either be on water level or on discharge compatibility. Particular care has to be taken in applying this form of schematization if water quality processes are to be included in the model.

In a model coupled along an almost horizontal plane, 2D grid cells are placed above the 1D domain, as shown in Figure 4. In this schematization, the de Saint Venant equations are applied only up to bank level. Above this level, the flow description in the 2D cell takes over. For relatively small channel widths compared to the 2D cell size, errors in neglecting the effect of momentum transfer at the interface are minor. This would be the case for a 1D-2D model built for the situation shown in Figure 5.

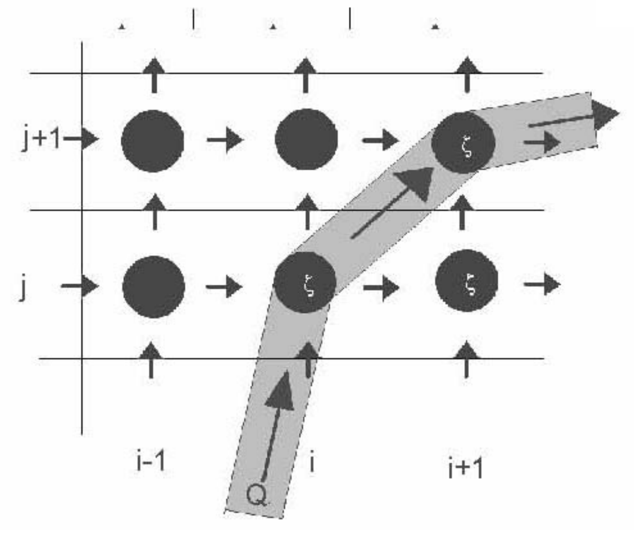

Figure 4 Coupling of 1-dimensional and 2-dimensional model domains in SOBEK

For wider channels it is recommended to modify each 2D cell depth used in the momentum equation by adding a layer defined by the local hydraulic radius for that part of the 1D cross-section which underlies a 2D cell. Further refinements are possible, including terms describing the momentum transfer between the 1D and 2D domains.

Numerical solutions are obtained by discretizing separately the 1D and 2D domains. Assuming that for both domains implicit numerical schemes are applied, the interface compatibility conditions can be modelled either as an explicit or an implicit link. Applying explicit links, subsequently the solutions for the 1D and 2D domains are generated. In a follow-up, exchange flows are computed and added as lateral flows at the next time step. Implicit links are based upon water level compatibility. These equations are then added to the complete sets of equations generated separately for the1D and 2D domains. There are many approaches to solving the complete set of equations. With the current state of the art, it is no longer necessary to apply for the1D domain different solvers for so-called simply or multiply connected channel networks. Similarly, in 2D there is no need anymore for alternating direction algorithms, as the efficiency of the conjugate gradient solvers has increased significantly over the past years.

As an example of coupling model domains via an interface in the horizontal plane, Delft Hydraulics has developed its combined 1D-2D package SOBEK. Various measures have been taken to make simulations very robust and efficient. For reasons of robustness the solver has strict time step controlling in order to avoid physically incorrect flow states. It also has a strict volume control, supporting robustness and not just accuracy. As an example of efficiency, the continuity equations for the 1D and 2D domains are combined into one single equation at points where 1D grid sections underlie a 2D cell, in order to reduce the number of numerical operations. As a first step in reducing the total number of equations, SOBEK eliminates all equations at velocity grid points. The second step in the solution algorithm is the elimination of a large number of unknowns by applying a minimum connection search between unknown water levels (special form of Gauss elimination). As a rule, this leads to an efficient elimination of nearly all unknowns of the 1D domain and a substantial number of unknowns in the 2D domain. This direct solver carries its elimination on, until nearly every second equation in the 2D domain has been eliminated. Beyond this point, it is more economical to apply the conjugate gradient solver to solve the remaining set of equations.

Apart from its efficiency, an additional advantage of eliminating nearly every second2D equation is the improved conditioning of the resulting matrix. This follows from the fact that elimination of an unknown water level at a 2D grid point has the effect of increasing the spatial distance between the remaining adjacent points, where water levels are still unknown. This, in turn, reduces Courant numbers and as a consequence, it leads to changed coefficients at the main diagonal of the matrix which is now more dominant in relation to the other diagonals, e.g. Verwey (1994).

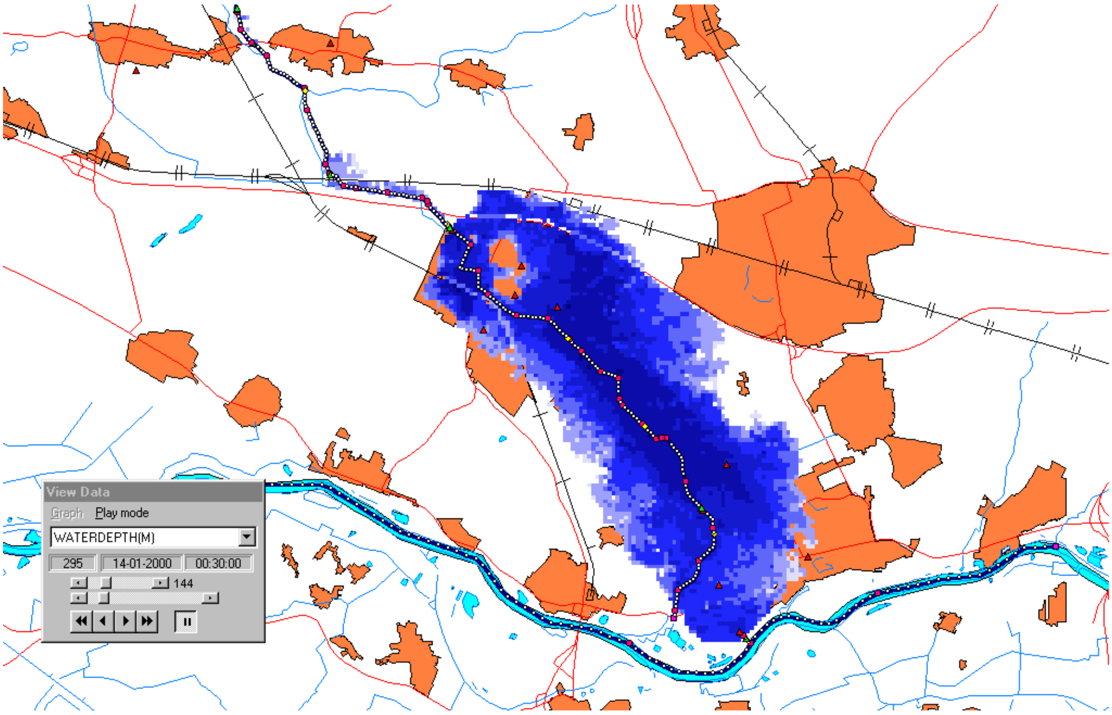

Figure 5 Flood modelling of the Vallei and Eem area, The Netherlands

An example of a combined 1D-2D model is shown in Figure 5. It represents the schematization of a model of the Eem Valley area in The Netherlands applied in a study of the potential effects of a River Rhine dike breach. This model has been used to provide information on warning lead times and flood depths for evacuation planning. The Rhine branch upstream of the breach has been modelled in 1D. At its upstream end a design hydrograph was specified, whereas the downstream boundary condition of this relatively short branch is given by a rating curve. Such a short downstream reach is permissible as the rating curve automatically corrects for most of the effects of flow deviated through the breach at this boundary. The breach itself has been described in 1D as a structure with a velocity dependent breach growth. North of the dike the 1D link discharges into the 2D domain, given by a 100 * 100 m grid with bottom levels derived from a digital elevation model and resistance coefficients derived from land use maps. Elevated roads and railways are presented as flow barriers by raising the underlying cell bottom levels up to the levels of these embankments. The resulting flood depths presented in Figure 5 clearly show the effect of the 1D channel in the schematization. Due to their greater depth, flood waves propagate faster in these channels than over land. Further downstream, this leads to first signs of the progressing flood wave already one or two days before the main flood arrives.

Final Remarks

Recent developments in numerical modelling offer great potential for a better planning and further development of the Mekong Delta water system. However, one of the principal barriers in the development of such numerically based support tools is the lack of good topographic data. This applies, in particular, to the Plain of Reeds. A realistic schematization of the hydraulic system requires an integrated 1-dimensionaland 2-dimensional (1D-2D) approach. Only in this way a support tool can be developed that offers more reliable results than the current VRSAP and ISIS models. The schematization is best defined on the basis of a separation of the 1D and 2Dmodelling domains via the horizontal plane. In this way a pure 1D model for the simulation of hydraulic problems during the dry period (e.g. salinity and other water quality issues) can easily be extended to an integrated 1D-2D model for flood simulations. Such models will be more correct than pure 1D models for the simulation of extreme scenarios, for which no measured data is available.

For the collection of accurate topographic data for the Mekong Delta the recent developments in LiDAR technology offer great potential. The recent developments in the automatic processing of collected data (e.g. demonstrated by the FLI-MAP® - Fast Laser Imaging and Mapping Airborne Platform system of Fugro) have made these techniques cost effective.

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