

# Predicting Flood Inundation and Risk Using GIS and Hydrodynamic Model: A Case Study at Eskilstuna, Sweden

(lead paper)

Xihua Yang and Bengt Rystedt

Department of Technology, University of Gävle, SE-801 76 Gävle, Sweden

Keywords: GIS, digital elevation model, flood, visualisation

## Abstract

This study is an attempt to develop an integrated methodology for flood prediction using geographic information systems (GIS) and hydrodynamic modelling and to obtain flood information for flood emergency planning. The feasibility of simulating a flood event along a river channel is explored in areas near residential development in Eskilstuna community, Sweden.

Hydrologically corrected digital elevation models (DEM) were created using ANUDEM algorithms available in ARC/INFO GIS (TOPOGRID Module). Other relevant databases (such as real estate, buildings, and river channels) were topologically corrected and attributed for analysis. These data were then used to prepare inputs to MIKE21, a hydraulic numerical modelling software tool, in the specific formats for the hydrodynamic modelling, and the outputs from MIKE21 were then transferred back to GIS for visualisation and analysis. Specific Arc Macro Language (AML) and C++ programs have been developed for these data conversion and integration. Snapshots at desired time steps and animations were generated in both the GIS and MIKE21 software. ARC/INFO GIS was used for data preparation, integration and analysis, and Arc View GIS was used to assist visualisation for end users. Field measurements were carried out to validate the hydrologic settings and assess the accuracy.

The results of this study show that integration of GIS and hydrodynamic modelling is an efficient way to predict flood and obtain flood information for emergency response planning and evaluation of the degree of risk posed to local community.

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## 1. Introduction

Estimation of flood inundation and its risk is increasingly a major task in relevant national and local government bodies in Sweden and world-wide. Prediction of flood inundation is not straightforward since the flood inundation extent is highly dependent on topography and it changes with time (dynamic). When bankful flow depth is reached in a flood event, water ceases to be contained solely in the main river channel and water spills onto adjacent floodplains. This consists a 1D hydraulic routing procedure for channel flow, 2D over floodplain to enable simulation of flood water depth and hence inundation extent. These make the flood prediction a very complex process in both spatial and temporal contexts. Conventional engineering methods are time consuming, and visual display of the planning scheme for a catchment is rudimentary.

These problems can be partially overcome by the integration of a hydrodynamic modelling tool such as MIKE21 with GIS. Thus the outputs from model can be used in GIS along with other spatial data for analysis and visualisation. Incorporating MIKE 21's capabilities with a GIS allow for analysis of the full impacts on flood extents, flood depths, flood damage of present or future (e.g., "WHAT IF" scenarios). Flood damage assessment from a cost/benefit analysis can also be linked to an optimisation module. The optimisation module allows for investigating different strategies for alleviating and diverting floods. At all stages of the integrated process model results can be presented to decision-makers in a clear and easily understandable formats.

**1.1 Study area:** This case study is a part of the project called KRIS-GIS® which started from an exercise called Kolinda. In Kolinda the area for the exercise was Mälardalen. One of the municipalities in Mälardalen is Eskilstuna, which is located about 100 km west to Stockholm. See Fig. 1. When the preliminary study for KRIS-GIS® started, Eskilstuna made eight scenarios over risks in the municipality. Flooding assessment is one of these consequences with a higher priority.

The Eskilstuna catchment area with available DEM has an average elevation of 20.5 m (MSL) ranging from 0 to 69.2 m (MSL). A subset area was selected along the river with an area of 84 km<sup>2</sup> (6 km by 14 km) and used as working area in the hydrodynamic model. The surface elevations in the working area range from 0.7 m to 58.9 m (MSL) with an average of 19.7 m (MSL). Such a subset is just large enough to represent the river and the surrounding

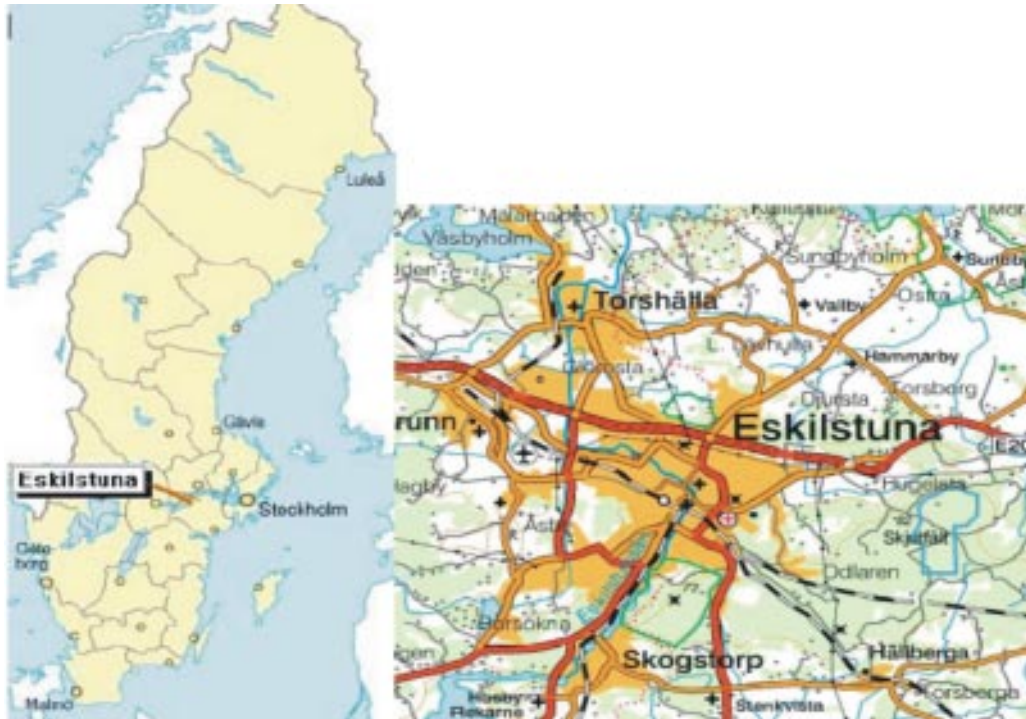


Figure 1: Study Area

surfaces so that the computing time is reduced to minimum in the hydrodynamic model but without sacrifice to information loss.

The river runs primarily from south to north between Hjälmaren Lake and Mälaren Lake with a total length of approximately 25 km. River elevations range from 23 m at the inlet (south) to 0 m (MSL) at the outlet (north). The river width at most locations is in the range of 50 to 80 m, and depth from 4 m to 10 m. There are 12 dams (including flood gates) along the river for water regulation and flood control. The river banks are normally very low; some part of the river is even higher than the ground surface. Most buildings and residential areas are within a buffer zone of one km from the river, thus subject to flood and pose great risk if there is a severe flood event.

## 2. Problem Statement

Spring and autumn floods frequently occur in northern and central Sweden which results in damage to property, crops and negative impacts on human welfare. It is of great value in the planning process at a regional and local level to be able to predict, prevent and remedy the effects of flooding in an efficient way. Modelling and simulations that combine the available data in an accurate way are crucial tools and form a basis for a suitable decision making system concerning civil emergency planning.

This study is to predict flooding area and the associated risks for a flood event using a GIS and hydraulic numerical modelling tool MIKE 21 (DHI, 2000a). It attempts to address these questions frequently asked in flood management and control:

- Which areas are to be flooded or at risk of a given flood event?
- What is the social and environmental cost of a flood?
- How soon will a flood reach a sensitive point?

The specific objectives of this study are to:

- develop methods and procedures for integrating GIS and hydrodynamic model (MIKE21);
- estimate and map the flooding areas and risks at a designed flood and
- implement these modules in a GIS for visualisation and informed decision making.

## 3. Methodology

**3.1 The Data Sets and Pre-processing:** There are generally two types of data sets that have been used in this study: spatial and non spatial data. Spatial data include digital elevation model (DEM), channel network, dams or flood gates, watershed boundary and buildings/properties. Non spatial data are inflow discharge, land/building values, weather data and channel geometric data.

Most of these data sets were available from the National Land Survey (NLS) of Sweden which had to be edited and preprocessed before these could be used in GIS and the hydrological modelling tool.

The DEM data received from the National Land Survey came in the form of ASCII files containing UTM coordinates and elevations in meters with 1 m vertical and 50 m horizontal resolutions. The DEM data were first merged to form the surface elevation for the whole study

area which is about 84 km<sup>2</sup> It is advantageous to combine the points into one file, rather than to process the files individually and later merge them on the GIS. This eliminates problems with edge effects. Then the merged DEM was further processed to remove peaks and sinks so that it is hydrologically correct for hydrodynamic modelling. The TOPOGRID module in ARC/INFO GIS was used to generate hydrologically corrected DEM (HYDRO58). The algorithm generates a DEM using an iterative technique of finite difference interpolation developed by (Hutchinson, 1989) which optimizes the flow model and maintains the integrity of the input data while simultaneously ensuring surface continuity. A

subset DEM (SUB50) was then created and resampled to 100 m (SUB100) and 150 m (SUB150) resolutions respectively for later use in hydrodynamic model. These DEM subsets were further merged with river elevation grids (RIV50, RIV100 and RIV150) to create combined surface elevation grids (SUBHD50, SUBHD100, SUBHD150) which represent both river and land surface elevations and are used further to prepare MIKE21 model inputs. These DEM grids are summarised in Table 1:

The building data came in Arc View Shape file with only line features. Specific procedures were developed to geo-code the attributes using the internal topological

**Table 1. Summary of DEM grids generated from original elevation data. DEM Grid (m)**

DEM Grid	Xmin (m)	Ymin (m)	No. of Rows	No. of Col.	Cell Size (m)	Elevation range (m)	Average elevation (m)
*HYDRO58	1529975	6574975	401	301	50	0 – 69.2	20.573
SUB50	1536000	6577000	280	120	50	0.7 – 58.9	19.746
SUB100	1536000	6577000	140	60	100	0.7 – 58.9	19.812
SUB150	1536000	6577000	93	40	150	0.7 – 58.9	19.806
SUBHD50	1536000	6577000	280	120	50	0.7 – 58.9	19.727
SUBHD100	1536000	6577000	140	60	100	0.7 – 58.9	19.754
SUBHD150	1536000	6577000	93	40	150	0.7 – 58.9	19.728

\*Note: HYDRO58 (the hydrologically corrected DEM) is the only grid needed as data source in the analysis and modelling, other grids can be generated from it using MIKE21.AML program or manual processing.

relationships and to convert into polygon format. Very tiny building features were removed but 99% of them remained. We found that these procedures are effective, and further editing was to be performed to get rid of non-building features. Then polygon topology was built and attributes information generated for further analysis. The building values were estimated and added into the attributes based on the type of building and their areas (sizes). The property data was also made available in Shape file (AY\_MILI.SHP) and its 'value' information in MS Access file (TAXERING.MDB). The MDB file was then joined with the property layer through the common identification (FNR\_FDS field) to create a property layer (AY\_MILI) with correct value information (including land, building and total values and the use) for each block. These were used in flood risk assessment later.

Channel network was created from the existing river data which are CAD drawing with double lines for river

representation. The main channel was digitized and all necessary information was encoded including river elevation (Z), sections with different discharges and special nodes representing locations of dams or flood gates. The main river channel layer (MAIN) was also rasterized (using elevation Z item) and merged with the DEM grids to create the combined surface elevation for hydrodynamic modelling. Dams and flood gates are stored as point data layer, but their locations are transferred on to the channel data layer (MAIN) for hydrodynamic modelling and network analysis. These data are useful as control points ("Source and Sink") in the hydrodynamic modelling. In addition, watershed boundary was generated from the hydrologically corrected DEM (HYDRO58). Contours, land use, orthographic aerial photo were also collected and used for visualisation and flood planning. These data layers are listed in Table 2.

**Table 2. List of GIS data layers prepared and used in the flood study.**

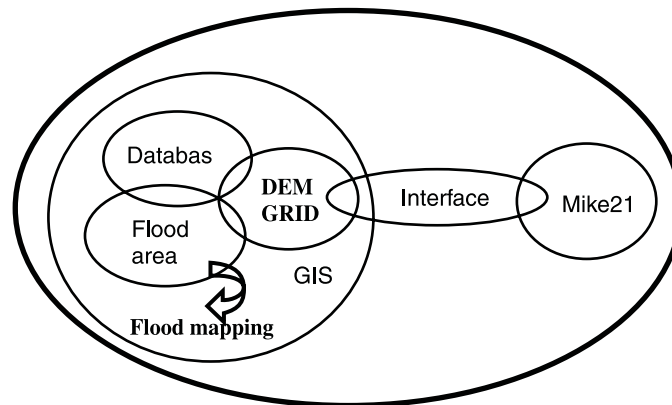
Coverage Name	Description	Usage
*AY MILI	Property data layer with values	Risk assessment
CONTOUR	Contour layer at 1 m interval	DEM creation and comparison
DAMS	Dams and flood gates	Hydrodynamic modelling
HUSL	Buildings	Risk assessment
*MAIN	Main river channel with	Hydrodynamic modelling
RIVER	River network	Network analysis
WATERSHED	Watershed boundary	Hydrologic modelling
ORTH	Orthographic aerial photo (IMG)	Visualisation

\*Note: that these data layers marked with \* are directly used in the analysis and modelling, others are used as ancillary data and for visualization.

**3.2 The Approach:** This research aims to develop an integrated approach incorporating a hydrodynamic model (MIKE21) with a GIS to predict a flood event in both spatial and temporal contexts. The research focus is, however, on the integration and the specialized data processing techniques to obtain flood information on 1) flood flow rates and discharges, 2) flooding inundating areas, 3) flood damage and risks. This information can be directly used for flood management and planning.

Generally, there are four types of integration methods: 1)

Embedding GIS-like functionalities into hydrological modelling packages; 2) Embedding hydrological modelling into GIS packages; 3) Loose coupling; 4) Tight coupling (Sui and Maggio, 1999). According to this classification, we chose a loose coupling method for this study since it suits our purpose and others are out of the scope of this study within our time frame (three months). In such integration, GIS and hydrologic model remain separate, but loosely linked through data input and output (Figure 2)



**Figure 2. Diagram of the integrated GIS and hydrodynamic modelling system.**

We chose MIKE21 for hydrodynamic modelling. MIKE21 is a two dimensional, finite difference hydrodynamic flow model available from the DHI Water & Environment DHI, 2001b). MIKE21 solves the vertically integrated equations of continuity and conservation of momentum in two horizontal dimensions. In addition, MIKE21 has a modular structure where water quality modules and sediment transport modules are available as add-on modules to the MIKE21 hydrodynamic module. ArcView (Version 3.2) has been used for visualisation. All outputs are transferred into ArcView and a flood project file (FLOOD.APR) has been created for easy query, visualisation and mapping. It is where the end user and manager can access the research outcomes for informed decision making and planning.

**3.3 Data Integration:** After the data pre-processing the hydrologically corrected elevation GRID, combined with the river elevation, was converted to an ASCII file with an information header using the GRIDASCII command. An AML program has been developed to perform all these data processing tasks and go all the way from DEM grid to produce an elevation XYZ input and an ASCII elevation grid (ASC) in negative values (as required by MIKE21 model), and resample to different cell sizes (e.g. 50, 100 and 150 m). The program also allows user's choice for the working area by selecting either the whole area or a subset. The XYZ elevation text file is to be used as the XYZ import file in the manual editing of MIKE21 bathymetry which is a time-consuming process. Alternatively, a C++ program along with a C filter provided by Dr Tom Heinzer from US Bureau of

Reclamation, was specifically designed for such translations between ARC/INFO and MIKE21 which converts the ASCII GRID file to a MIKE21 array file (DT2 file). In addition, this program also adds Land Value and boundaries to the normal ASCII grid. The output from the program can then be directly visualized and manipulated within the MIKE21 software and used as DT2 input file in the hydrodynamic module. By using such automated processing, considerable time can be saved by avoiding the manual data editing of bathymetry and boundary definition.

The steps involved in the study include 1) convert the MIKE21 output (DFS2) to ARC/INFO ASCII grid file with an appropriate header; 2) convert to ARC/INFO grid (ASCII GRID); 3) convert to polygon (GRIDPOLY); 4) dissolve and build topology to create a new polygon which represents the flood area (DISSOLVE). This polygon was superimposed (CLIP) with the real estate data layer to find out the affected properties and the damage. Part C of the AML program (MIKE21.AML) is specially designed for the above processing which generates the flood area polygon and the affected property data layer with value attributes after the MIKE21 output has been transferred into GIS through another C filter (M212ASCII) from Dr Tom Heinzer at US Bureau of Reclamation.

**3.4 The Flowchart:** The following flowchart in Fig. 3 may be characterised into the following eight steps:

- 1) Prepare hydrologically corrected DEM; 2) Prepare

other data sets (real estate, river channel, etc.) and their attributes; 3) Generate MIKE21 bathymetry input (DT2); 4) Run MIKE21 hydrodynamic model; 5) Transfer the model

results to ARC/INFO and raster to polygon conversion; 6) Overlay with property data layer to extract affected properties; 7) Analysis and mapping; and 8) Visualisation.

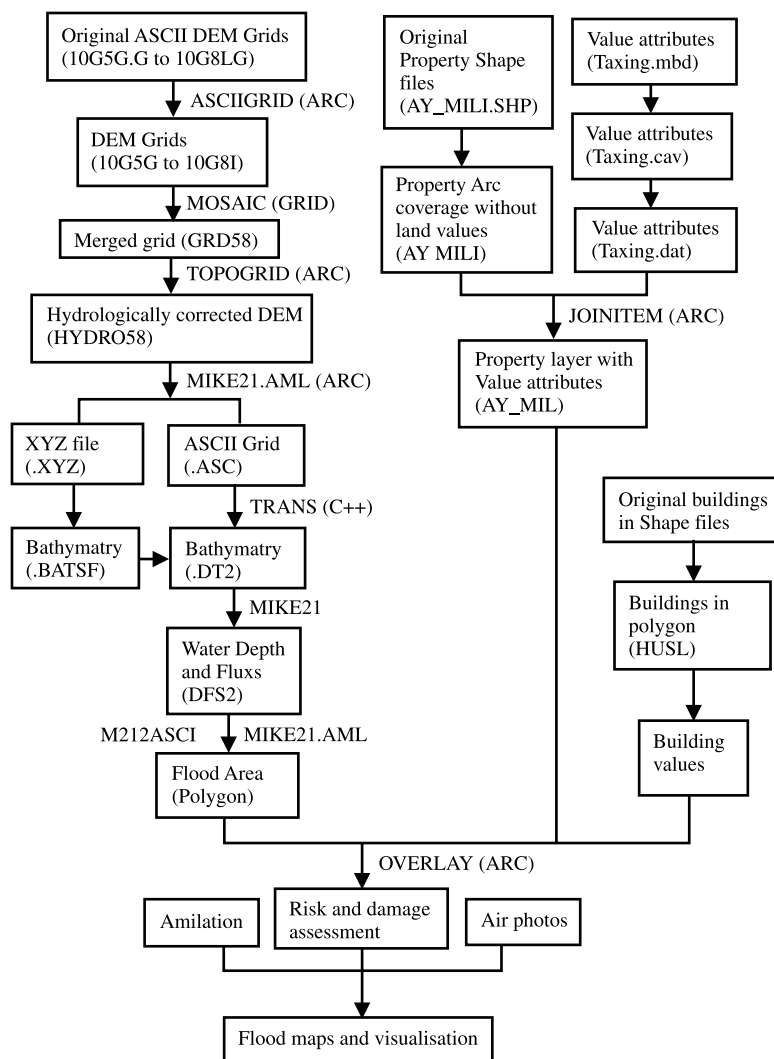


Figure 3. Flowchart of the data processing and modelling procedures.

#### 4. Results and Discussions

Due to uncertainty of some hydrological parameters (such as Manning's coefficient), various hydrological settings are tested in the hydrodynamic model. The open boundary locations were chosen at the river inlet and outlet points which go through the selected working area (in and out). The cell size was set to 50, 100 and 150 m respectively; Manning resistance set to 5, 10 and 33 m<sup>1/3</sup>/s (default value is 33 m<sup>1/3</sup>/s); flux at inlet set to 112 CMS based on the average 100 year flood discharge rates, and level at outlet set to -59.3 m based on the elevation at that point (subtracted by the maximum elevation, 60, so that all elevations are negative numbers). Dry and flooding value was set to 0.2 and 0.3, but increased if the model became unstable (e.g. blow-up problem).

The model outputs are Water Depth (m), P and Q Fluxes (m<sup>3</sup>/s/m). Simulation results show that, assuming a 100 year flood event, P and Q fluxes range from 0 to 1.1 m<sup>3</sup>/s/m, the water depths range from 0 up to 4 m. Model run times varied from 30 to 180 minutes depending on the settings. An animation of a resultant water depth is shown in figure 4.

The water depth output from the model was converted into ARC/INFO grid, then the flooded area using internal ARC functions. By overlaying the resultant polygon of flooding area with the real estate data, the flooding affected properties were extracted which was in turn used to estimate the damages or risks. These were done through the Part C in the AML program (Mike21.aml).

Table 3 lists the GIS output data layers generated in this study. The first letter S indicates it is a subset, the

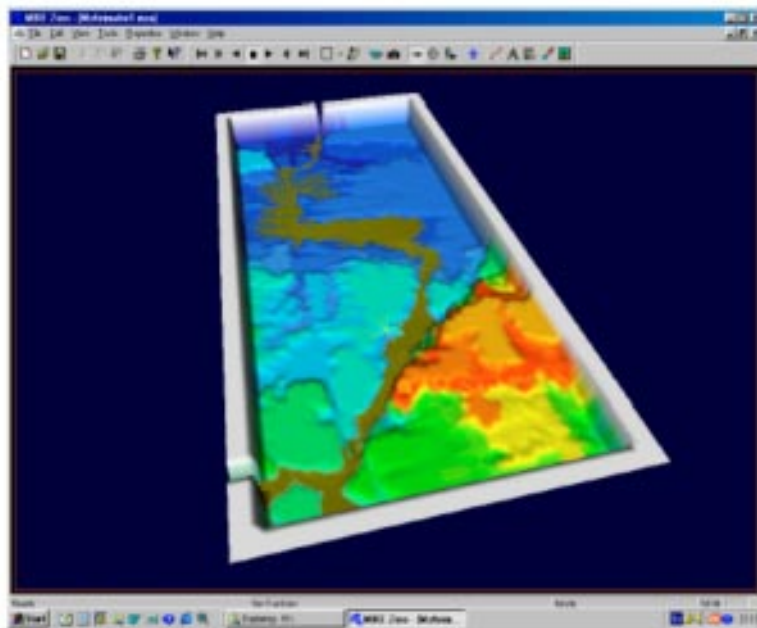


Figure 4. An Animation of the flood flow using Mike21 Animate.

following number indicates the cell size, then the Manning's resistance number. In the actual GIS databases, these names ended with either 'poly' or 'clip' (e.g., S50r5poly, S50r5clip) indicating a polygon flood

area data layer and a clipped property data layer (the resultant data layer by overlaying flood area with the property data layer).

Table 3. Comparisons of model results using different settings.

Output GIS data layer	Cell Size (m)	Manning number used	Flood area (km <sup>2</sup> )	Number of properties affected	% property affected	land value (Kr)	House value (Kr)	Total value (Kr)
S50r5	50	5	14.00	2183	13.14	1348936	3367012	4715948
S50r10	50	10	12.49	1934	11.64	1380686	3318924	4699610
S50r33	50	33	7.69	1285	7.73	1008046	2591532	3599578
S100r5	100	5	13.71	1695	10.20	1102290	3068089	4170379
S100r10	100	10	12.86	1593	9.59	1077562	2944780	4022342
S100r33	100	33	10.57	1261	7.59	844396	2414893	3259289
S150r5	150	5	15.80	2267	13.65	1520117	3635195	5155312
S150r10	150	10	13.30	1690	10.17	1172278	2989935	4162213
S150r33	150	33	14.04	2012	12.11	1034886	3000778	4035664

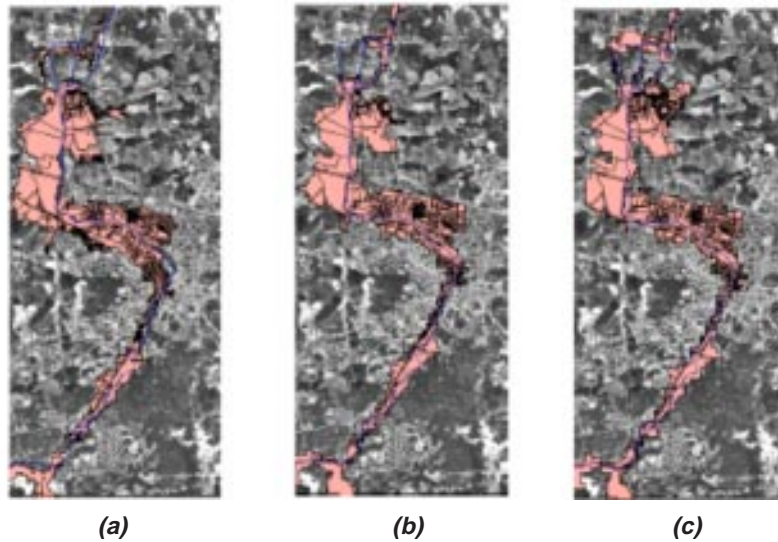
From these test settings, it seems that a cell size of 100 m best represents the river (with a width ranging from 50 to 80 m) and has good stability during the model run. A cell size of 50 m causes 'Blow Up' problem in most cases since it has the narrow channel and the connectivity problem. The model has a stable run with a 150 m spacing, but it does not best represent the actual size (width) of the river channel. The comparison is graphically shown in Figure 5.

Due to uncertainty and lack of measurements, we used several possible Manning's resistance numbers (1 to 33) in the hydrodynamic model. Note that in MIKE21 using a greater number decreases the bed resistance and model runs less stable, a small number increases the bed resistance and model runs more stable (for details refer to DHI, 2001b). Figure 6 shows the comparisons using

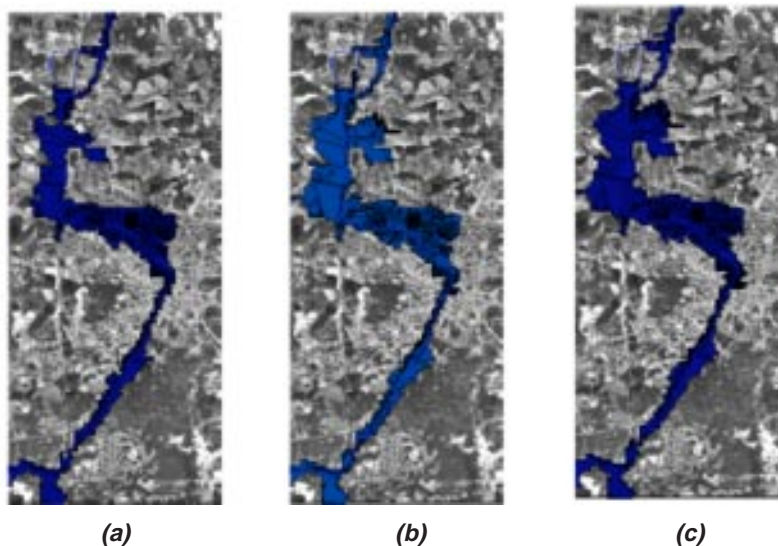
different Manning's numbers with all other settings being the same.

These outcomes have been generated in this study:

- Topologically and hydrologically corrected GIS flood databases
- AML and C Programs for data processing, integration and data conversions
- Estimated flood area of a flood event (100 year flood) at a given time
- Time series of inundation extent of a flood event
- Buildings lands subject to flood and their associated values
- A series of flood maps, visualisation and report



**Figure 5. Comparisons of affected areas using different cell sizes (spacing), where a is simulated flood area with spacing 50 m, b is the simulated flood area with spacing 100, c is the simulated flood area with spacing 150. The background is an aerial photo and blue line is the main river channel.**



**Figure 6. Comparisons of affected areas with different Manning's resistance numbers, where a is the result using a Manning's number of 33, b of 10, c of 5. The background is an aerial photograph and blue line is the main river channel.**

The risk assessment was also made by the number of affected buildings (mostly residential houses) which might be useful for insurance and real estate companies. There are 17279 buildings in Eskilstuna region near the river and there are 2494 buildings to be affected in a 100 year flood (using a cell size of 100 m and a Manning's number 33) which accounts for a percentage of 14.4% by building number. The affected buildings (within the polygon) are shown in Figure 7.

There were no real means to calibrate the simulations. Usually when flood events occur, flow and stage data are rarely recorded. However, we have tried to implement the best available modelling and GIS technology available to us, tempered of course by cost and resources. The modelling methods described in this report appear to

give us a reasonable description of what may occur in designed flood scenarios (e.g., 100 year flood), and we will be applying this technology toward future emergency management planning endeavours.

It must be pointed out that our problem (river flooding) is not a typical MIKE21 problem which mainly deals with hydraulic and related phenomena in lakes, estuaries, bays, coastal areas and seas. To make use of this model for river flooding, great care has to be taken to prepare the data and model settings so that the model understand them and treats as recognized modelling environment (e.g., lakes). We were aware that a new module, MIKE FLOOD, was about to be released by the time of the completion of this research. However, such module is still based on 1D modelling technique, using a 2D model may



**Figure 7. The affected buildings (within the polygon) with a 100 year flood event.**

Note that this was estimated using the buildings data layer (HUSL) rather than the real estate data layer.

still have its advantages in flooding simulation.

When using the MIKE21 model, a dimensionless flow parameter comes into play called the Courant number, defined as  $C = c \cdot (\Delta t / \Delta x)$  where  $\Delta t$  is the time step,  $\Delta x$  is the grid spacing, and  $c$  is the celerity, defined by  $c = \sqrt{g \cdot h}$  where  $g$  is the gravitational constant and  $h$  is the average water depth. The Courant number describes how many grid points the celerity 'information' propagates within one time step. In MIKE21 when modelling flow, the Courant number should be kept under 5 (in general). For a cell size of 100 ( $\Delta x = 100$  meters), the constraint on  $\Delta t$  was usually around 10 seconds or less to meet the Courant condition.

Three-dimensional effects dominate the leading edge or front of a flood wave, and these regions are characterized by substantial turbulence, which implies considerable energy dissipation. We are not actually modelling these effects, and it is uncertain how much error this introduces to what would be the 'actual' propagation of the wave front. This is a considerable concern, because the leading edge as a function of time is one of the main actors used in emergency management planning. DHI is currently researching methods to address this area.

To simplify the modelling processing, we assumed that all flood gates or dams are fully open in a flood event, but this may be not true in a real flood scenario. Ignorance of the presence of dams or gates may result in changes of flood volume and directions. Therefore, further effort should be made to include dams and flood gates in the flood simulation.

## 5. Conclusions and Further Directions

During the execution of the flood project the automated process (AML and C++ programs) developed in this

study has played an important role in maintaining and processing the variety of data sets that have been used for the modelling activities. With the automated processing, the time-saving is one of the biggest advantages. The 'loose coupling' approach appears to be adequate for such a study within the limited timeframe. However, in further studies, other integration methods, such as the conceptual consideration in the integration, should be considered so that the integration is more generic and applicable to other relevant studies and areas.

The major problem with MIKE21 in this study is the model stability or 'Blow-up' problem. The model stability is affected by too many factors such as boundary conditions, bed resistance (Manning's number), Courant number (spacing and time steps) and flooding/drying specifications. Great care and time need to be taken to carefully choose all these factors.

To best represent the river and have a stable run of model (a lower Courant number), we recommend a cell size of 100 m which reasonably represents the river and achieves stable model runs in most cases. The current DEM has 1 meter vertical resolution which is too coarse for such a modelling activity, a finer DEM (e.g., up to 0.1 m vertical resolution) would greatly improve the model quality.

The C++ Translators between MIKE21 and ARC/INFO developed in this study worked very well. The first author has developed an integrated drainage network analysis system (IDNAS) (Yang et al., 2000a and 2000b). Such system simulates the water flows in a constrained channel network system. Integration of such a 1D channel network flow system with a 2D overland flow model will enable the dynamical simulation and visualisation of the water flow in both normal and flooding situations. This will add extra benefit to routine water management and planning for such tasks as pollution movement simulation and discharge capacity assessment.

## 6. Acknowledgements

This research was supported by grants from the Civil Emergency Planning (ÖCB). A three month test license of Mike21 software was generous provided by the DHI Sweden at Växjö. Authors thank Mr Dick Karsson from DHI Sweden in Göteborg and Mr Tahsin Yacoub from Swedish Meteorological and Hydrologic Institute (SMHI) at Norrköping for their help and time with MIKE21 model and hydrologic settings. Authors thank Dr Qingyuan Li, visiting fellow from Chinese Academy of Surveying and Mapping (CASM) for his help with C++ programming, and Dr Tom Heinzer from US Bureau of Reclamation for providing his C filters.

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