Predicting Flood Inundation and Risk Using Geographic Information System and Hydrodynamic Model

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Abstract
This study aims to develop an integrated approach to obtain flood inundation and risk information for flood emergency planning using geographic information systems (GIS) and hydrodynamic modeling (MIKE21). Hydrologically corrected digital elevation models (DEM) were created using specific spatial interpolation method, then used to prepare bathymetry inputs to the hydrodynamic modeling. The outputs from the model were then transferred back to a GIS for flood risk assessment and visualization. Flood maps, snapshots and animations at desired time steps were generated for informed decision marking for government and insurance industry. ARC/INFO GIS is used for data preparation, integration and analysis, and specific Arc Macro Language (AML) and C++ programs have been developed for the data conversion and integration. This study shows that integration of GIS and hydrodynamic modeling is an efficient way to obtain flood information for emergency planning and evaluation of the degree of risk posed to a local community.

I. INTRODUCTION

Spring and autumn floods frequently occur in northern and central Sweden that result 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. Modeling 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 (Kjelds and Muller, 1999 [6]).

Estimation of flood inundation and its risk is increasingly a major task in relevant national and local government bodies in Sweden and worldwide. 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 spills onto adjacent floodplains. This consists a one-D hydraulic routing procedure for channel flow, 2D over floodplain to enable simulation of floodwater 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 (Garrote and Bras, 1995 [3]; and Thumerer *et al.*, 2000 [8]). Although recent trends show improvements in visualization in some of these computer simulation models, there are still significant limits in spatial data handling and integration that are essential in flood risk assessment and emergency planning.

These problems can be partially overcome by the integration of hydrodynamic model with Geographic Information Systems (GIS). Thus the outputs from model can be used in GIS along with other spatial data for analysis and visualization (Thumerer *et al.*, 2000 [8]). Incorporating Danish Hydraulic Institute (DHI) Water & Environment MIKE 21's (DHI, 2000a [1]) 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.

This study is to predict flooding area and the associated risks for a flood event using a geographic information system and hydraulic numerical modeling tool MIKE 21 (DHI, 2000a [1]). It attempts to address these commonly asked questions 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? and
- How soon will a flood reach to a sensitive point?

The specific objectives of this study are to:

- develop methods and procedures for integrating GIS and hydrologic model (MIKE21);
- estimate and map the flooding areas and risks at a designed flood level (e.g. 100-year); and
- implement these modules in a GIS for visualization and informed decision making.

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II. STUDY AREA

This case study is a part of the national wide project called KRIS-GIS® which started from an exercise in Mälardalen. One of municipalities in Mälardalen is Eskilstuna, which is located about 100 km west to Stockholm. 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 study area is a subset of the Eskilstuna catchment (see Figure 1) at its low reach with an area of 84 km^2 (6 km by 14 km) which was used as the working area in the hydrodynamic model. The surface elevations in the working area range from 0.7 m to 58.9 m (Mean Sea Level, MSL) with an average of 19.7 m (MSL). Such a subset is just large enough to represent the Eskilstuna River and the surrounding surfaces so that the computing time is reduced to minimum in the hydrodynamic model but without sacrifice to information loss.

The Eskilstuna 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 (MSL) at the inlet (south) to 0 m (MSL) at the outlet (north). The river width at most locations is at the range between 50 m to 80 m, and depth from 4 m to 10 m. There are 12 dams (include floodgates) along the river for water regulation and flood control. The riverbanks are normally just about one or two meters above the river, some sections of the river are even higher than the adjacent ground surfaces. Most buildings and residential areas are within buffer distance of one kilometer from the river, thus subject to flood and pose great risk if there is a severe flood event.

III. FLOOD DATABASE DEVELOPMENT

We developed a comprehensive flood database to support this research using Arc/Info GIS. The spatial components include digital elevation model (DEM), channel network, dams or floodgates, watershed boundary and buildings/properties. Nonspatial components include inflow discharge, land/building values, weather and channel geometry. Most of these data sets were originally from the National Land Survey (NLS) of Sweden at the time of the project commencement. The spatial data sets were then edited and topologically corrected before they were used in GIS and hydrodynamic modeling.

DEM is crucial and most important among the spatial data sets. The DEM used in this study came in the form of a series of ASCII grid files containing UTM coordinates and elevations in meters with 1 m vertical and 50 m horizontal resolutions. These DEM files were first merged to form the surface elevation for the whole study area. Then the merged DEM was further processed to remove peaks and sinks so that it is hydrologically sound for hydrodynamic modeling. The

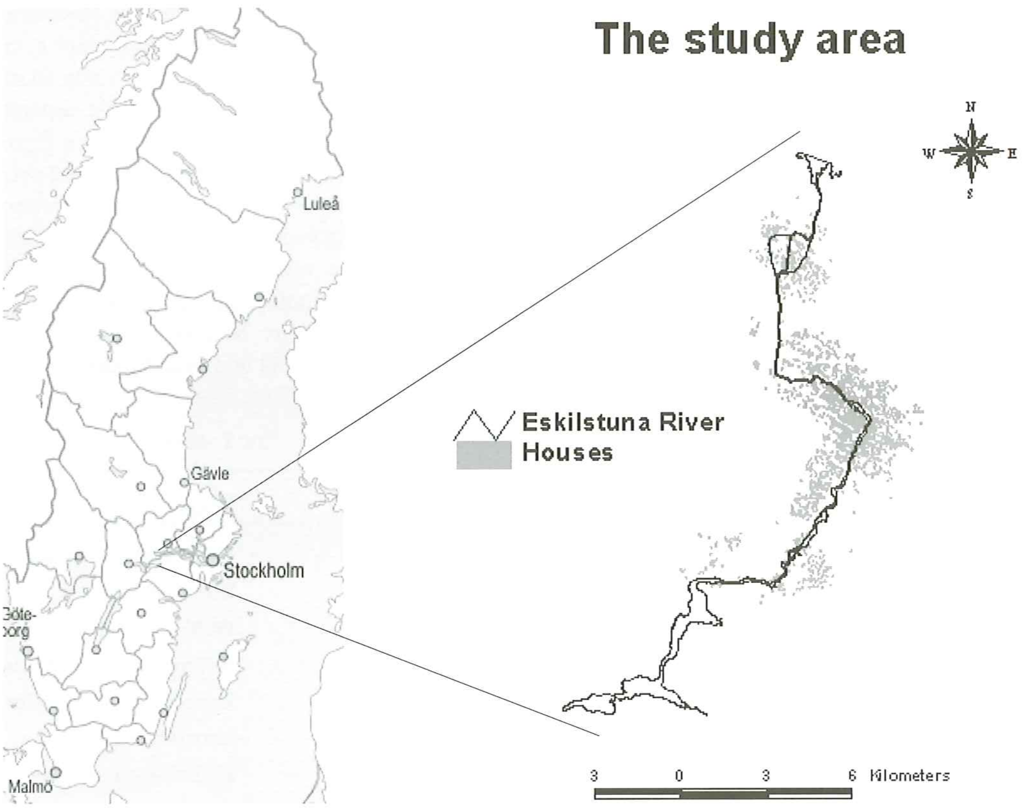

Figure 1. The study site at Eskilstuna, Sweden. The left map indicates the general location of the study area in central Sweden and the right one is an enlargement showing the Eskilstuna River and surrounding buildings.

TOPOGRID module in ARC/INFO GIS was used to generate hydrologically corrected DEM. The algorithm generates a DEM using an iterative technique of finite difference interpolation developed by Hutchinson (1989 [5]) that optimizes flow model and maintains the integrity of the input data while simultaneously ensuring surface continuity. DEM grids were then resampled to 100 m and 150 m resolutions respectively for later use in hydrodynamic model. These DEM grids were further merged with river elevation grids at the same resolutions to create combined surface elevation grids which represent both river and land surface elevations and were further used to prepare MIKE21 model inputs (Bathymetry).

The property (building and land) data came in ArcView Shape file with only line features. Specific procedures were developed to geocode the attributes using the internal topological relationships and to convert into polygon format. Further editing was performed to remove non-building features and those very tiny ones. Then polygon topology was built and attribute information generated for further analysis. However, the property 'value' information came separately with a MS access file (MDB). The MDB file was then joined with the property layer through the common identification to create a property layer with correct value information (including land, building and total values and the use) for each block. These are to be used in flood risk assessment later.

Channel network was created from an existing river map which are CAD drawing with double lines for river representation. The main channels (center lines) were digitized and all necessary information was encoded including river elevation (Z), sections with different discharge rates (e.g. W100 and WDIM), and special nodes representing locations of dams or floodgates. The main river channel layer was also rasterized (using elevation Z item) and merged with the DEM grids to create the combined surface elevation for hydrodynamic modeling.

Dams and floodgates are stored as point data layer, but their locations are transferred on to the channel data layer (MAIN) for hydrodynamic modeling and network analysis. These points are used as control points ("Source and Sink") in the hydrodynamic modeling.

In addition, watershed boundary was generated from the hydrologically corrected DEM. Contours, landuse, orthographic aerial photo were also collected and used for visualization and flood planning. These data layers are list in Table 1.

IV. METHODS AND PROCEDURES

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) flood inundating areas, 3) flood damage and risks. These information can be directly used for flood management and planning such as 1) evaluating flood control practices; 2) developing and screening flood management plans; and 3) predicting the downstream movement of flood and locate the buildings or properties are likely to be affected.

Generally, there are four types of integration methods: 1) Embedding GIS-like functionalities into hydrological modeling packages; 2) Embedding hydrological modeling into GIS packages; 3) Loose coupling; 4) Tight coupling (Sui and Maggio, 1999 [7]). 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. In such integration, GIS and hydrodynamic model remain separate, but loosely linked through data input and output (see Figure 2). This is a modular approach, thus more generic, and every module can be easily replaced and updated once a better one becomes available. In this study, the system includes the GIS, the hydrodynamic model (MIKE21), GIS databases and interfacing executable programs. Most of these programs were developed using Arc Macro Language (AML) and C++ running in ARC/INFO and in a Window's environment.

Table 1. List of GIS database prepared and used in the flood study.

Data Type	Description	Usage
*DEM	Hydrologically corrected DEM	Hydrodynamic modeling
*Property	Property data layer with values	Risk assessment
Contour	Contour layer at 1 m interval	DEM creation and comparison
Dams	Dams and floodgates	Hydrodynamic modeling
*Channel	Major river channels (center lines)	Hydrodynamic modeling
River	River networks	Network analysis
Watershed	Watershed boundary	Hydrologic modeling
Air photos	Ortho-rectified aerial photo	Visualization

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

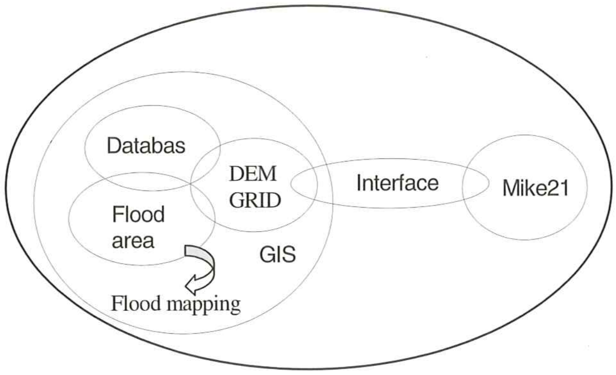

Figure 2. Diagram of the integrated GIS and hydrodynamic modeling system.

We chose ARC/INFO GIS since it is a professional GIS package and fully functional. It supports spatial editing, topology building, vector and grid modeling, macro language, network analysis and data import and export. These functions were used intensively in this study for spatial data preprocessing (as discussed in Section III), vector and grid data editing, programming, and data conversion. We used ARC/INFO version 7.2.1 running in a Window's NT platform.

We chose MIKE21 for hydrodynamic modeling. MIKE21 is a two dimensional, finite difference hydrodynamic flow model available from the DHI Water & Environment (DHI, 2001b [2]). MIKE21 solves the vertically integrated equations of continuity and conservation of momentum in two horizontal dimensions. We chose a two-dimensional flow model since we realized that one-dimensional models were not adequate to describe certain types of terrain, such as flood plain areas, overland topography, split flow scenarios, etc. 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.

In addition, ArcView (Version 3.2) was used for visualization and end user program development. All outputs were transferred into ArcView and a flood project file has been created for easy query, visualization and mapping. It is where the end user and manager can access the research outcomes for informed decision making and planning, an initial form of a flood decision support system (FDSS).

After the data preprocessing as presented in previous section, 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 (MIKE21.AML) has been developed to perform all these data processing tasks and go all the way from standard 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, 50m, 100m and 150m). 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 process for MIKE21 Bathymetry input, which is a time-consuming process. Alternatively, a C++ program (Trans.cpp) was specifically designed for such translations between ARC/INFO and MIKE21 which converts the ASCII GRID file to a MIKE21 array file (DT2 file) with boundary settings and allows batch processing. In addition, this program also adds a Land Value and boundaries cells (around the working area) 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 (see Figure 3). By using such automated processing, considerable time can be saved by avoiding the manual data editing of Bathymetry and boundary definition.

In order to present and study simulation results of the hydrodynamic modeling in the ARC/INFO environment, procedures have also been made that allow for import of MIKE21 results to ARC/INFO where they can be used for further analysis and visualization together with other geo-data set. These procedures include 1) convert the MIKE21 output (DFS2) to ARC/INFO ASCII grid file with an appropriate header; 2) convert to ARC/INFO grid (ASCIIGRID); 3) convert to polygon (GRIDPOLY); 4) dissolve and build topology to create a new polygon which represents the flood area (DISSOLVE). This polygon was overlayed (CLIP) with the real estate data layer to find out the affected properties for the damage assessment. The AML program (MIKE21.AML) performs all the above processing that generates the flood area (polygon) and the affected property data layer with value attributes after the MIKE21 output has been transferred into GIS using a C filter (M212ASCI). The whole data processing and modeling procedures are illustrated in Figure 4.

V. RESULTS AND DISCUSSIONS

In this study, various hydrological settings were tested in the hydrodynamic model. The open boundary locations were chosen at the river inlet and outlet points which go through (in and out) the selected working area. The cell size was set to 50 m, 100 m and 150m respectively; Manning resistance set to 5, 10 and 33 $m^{1/3}/s$ (default value is 33 $m^{1/3}/s$); Flux rate 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' problems).

The model outputs are Water Depth (m), P and Q Fluxes ($m^3/s/m$). Simulation results show that, assuming a 100-year flood event, P and Q fluxes range from 0 to 1.1 $m^3/s/m$, the water depths range from 0 up to 4 meters. Model run times varied from 30 to 180 minutes depending on the settings. An animation of a resultant water depth is show in Figure 5.

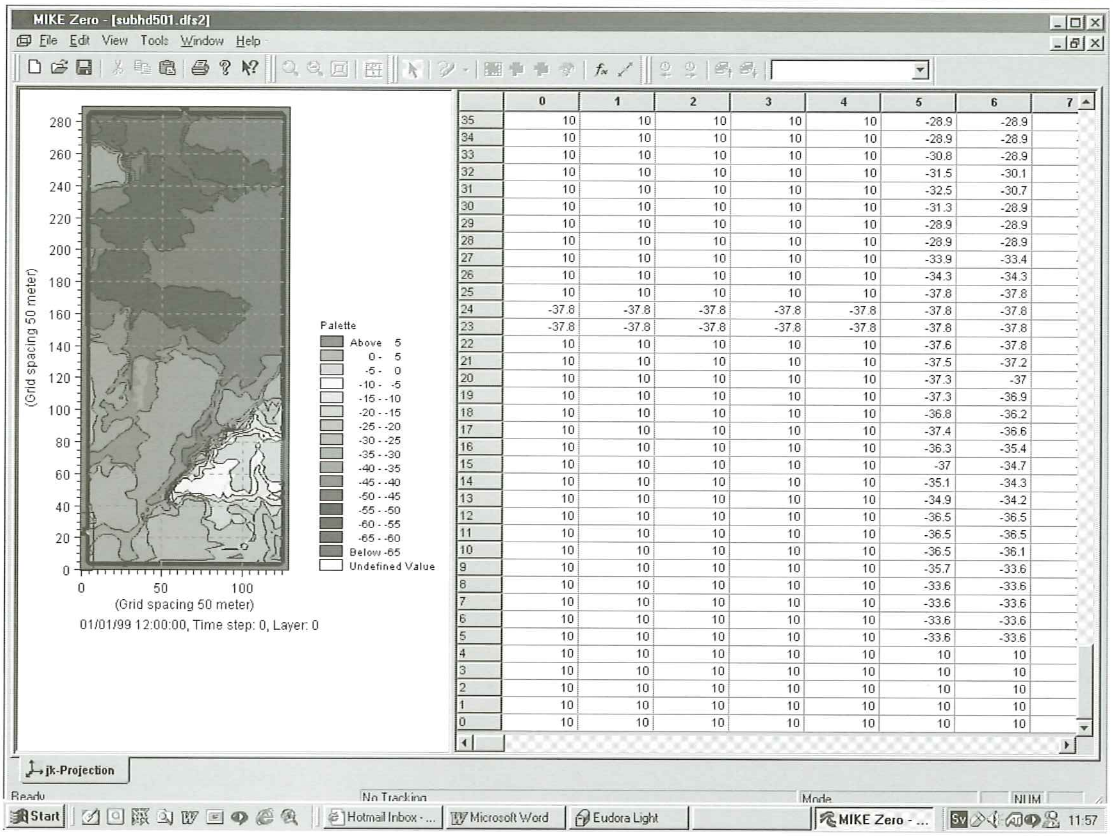

Figure 3. An example Bathymetry input (DT2) generated using C++ program.

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 property data, the flooding affected properties were extracted which was in turn used to estimate the damages or risks. These were done through the AML program (MIKE21.AML). Table 2 lists the GIS output data layers generated in this study.

From those test settings, it seems that a cell size of 100 m best represents the river 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 150 m spacing, but it does not best represent the actual size (width) of the river channel. The comparison is graphically showed on Figure 6.

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 [2]).

Table 2. Comparisons of model results using different hydrologic settings.

Output GIS data layer	Cell Size (m)	Manning number used	Flood area (km^2)	Number of properties affected	Property affected (%)	land value (Kr)	House value (Kr)	Total value (Kr)
S50R5	50	5	14	2183	13.14	1348936	3367012	4715948
S50R10	50	10	1249	1934	11.64	1380686	3318924	4699610
S50R33	50	33	7.69	1285	7.73	1008046	2591532	3599578
S100R5	100	5	13.71	1695	10.2	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	15.8	2267	13.65	1520117	3635195	5155312
S150R10	150	10	13.3	1690	10.17	1172278	2989935	4162213
S150R33	150	33	14.04	2012	12.11	1034886	3000778	4035664

Note: The first letter 'S' in the output GIS data layer indicates it is a subset, the following number indicates the cell size, then the Manning's resistance number after the letter 'R'.

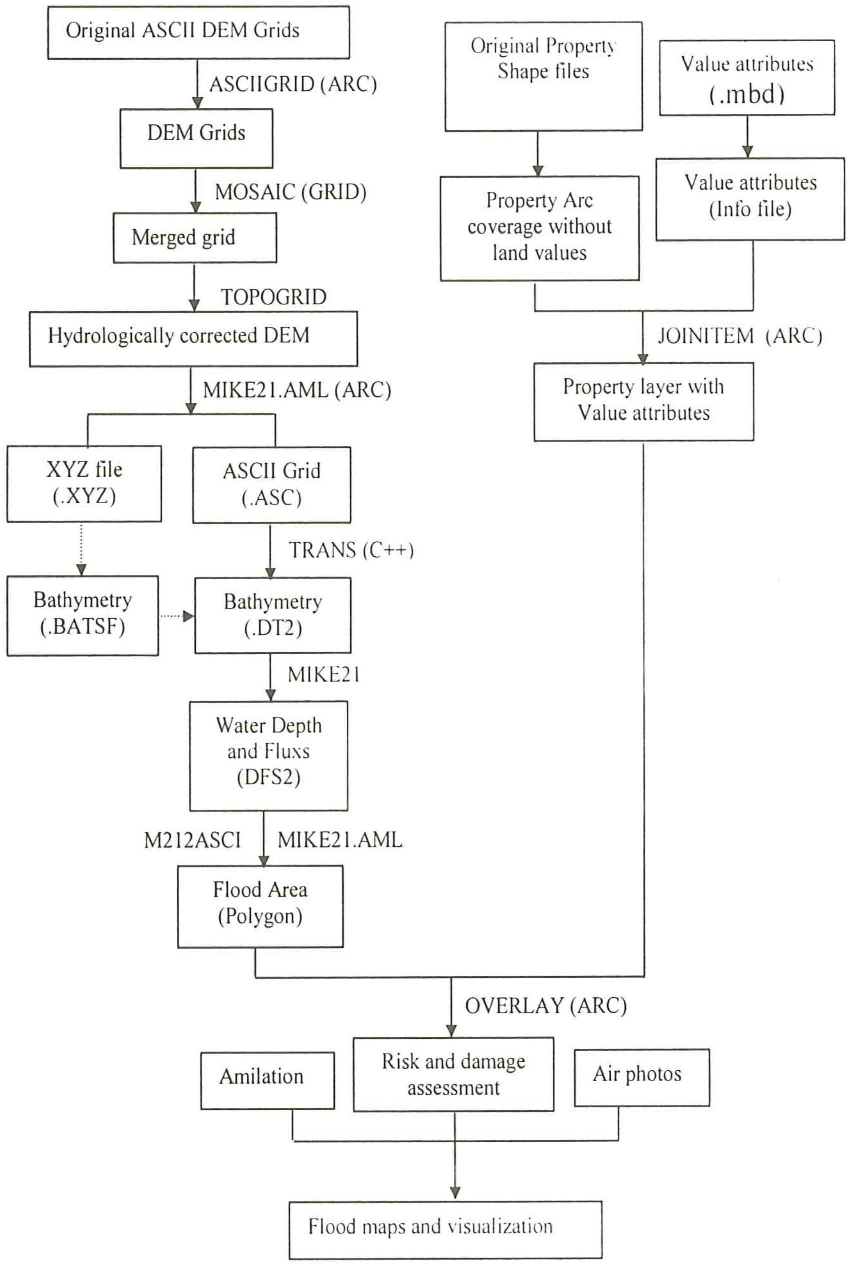

Figure 4. Flowchart of the data processing and modeling procedures.

Figure 7 shows the comparisons using different Manning's numbers but all other settings are the same.

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. In addition, this pilot study also identified and assessed the necessary data sets and their accuracy for emergency planning for a community in a flood event. These include such issues as data types, scales, accuracy, formats, attributes and standards that are recommended for similar projects in other communities.

Note that river flooding is a not a typical MIKE21 problem since the model 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 treated as recognized modeling environment (e.g, lakes). We were aware that a new module, MIKE FLOOD from DHI Water & Environment, was about to release by the time of the completion of this research. However, such module was still based on 1D modeling techniques, and using a 2D model is more appropriate and has its advantages in flooding simulation in a floodplain

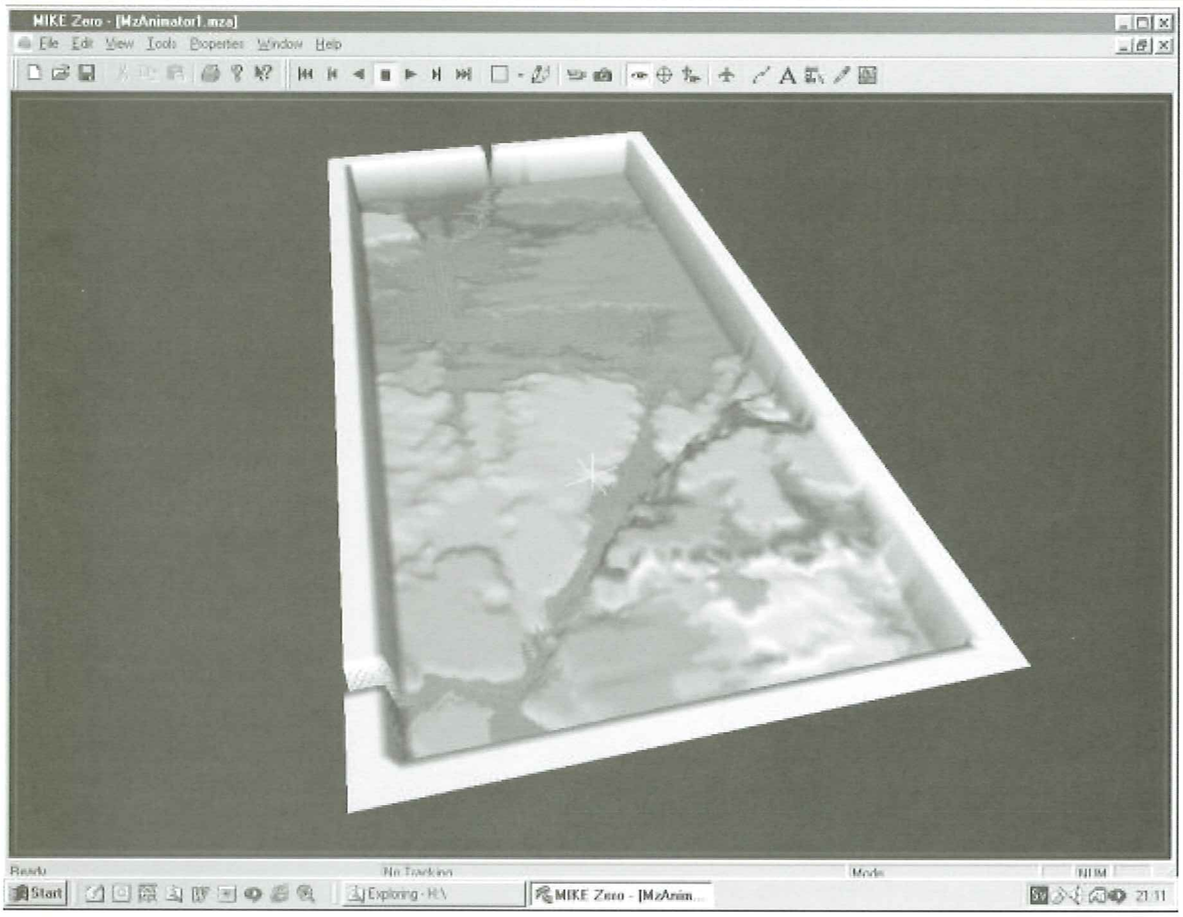

Figure 5. An animation of the flood flow using Mike21 Animate.

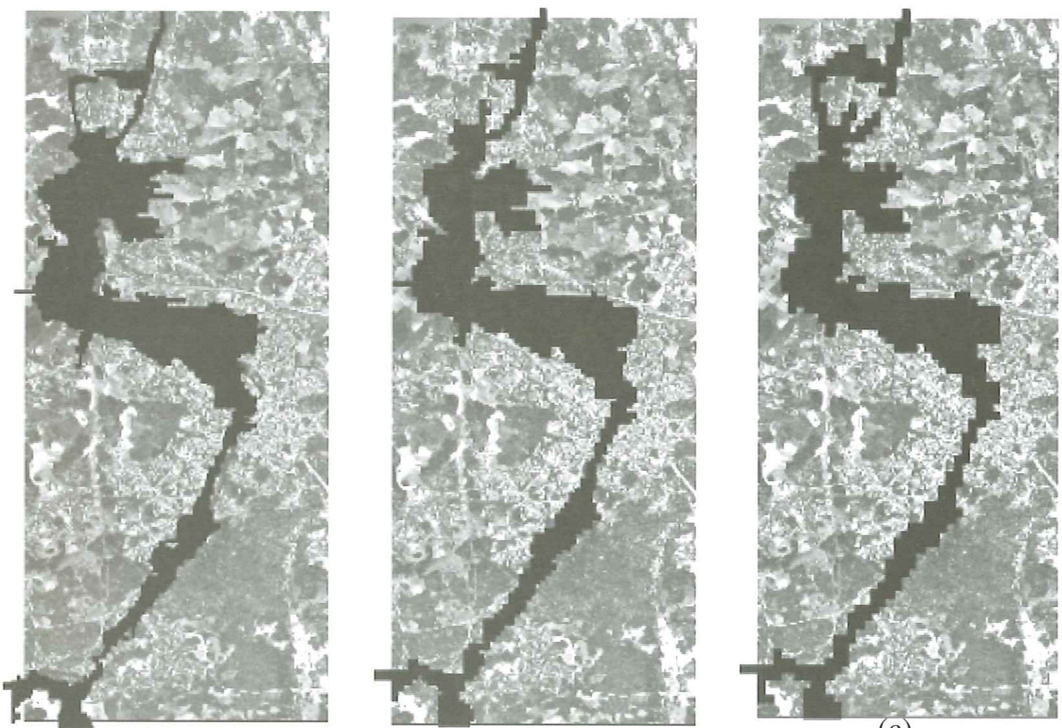

Figure 6. Comparisons of affected areas using different cell sizes (spacings), where *a* is simulated flood area with spacing 50 m, *b* 100 m, and *c* 150 m. The background is an aerial photograph of the study area.

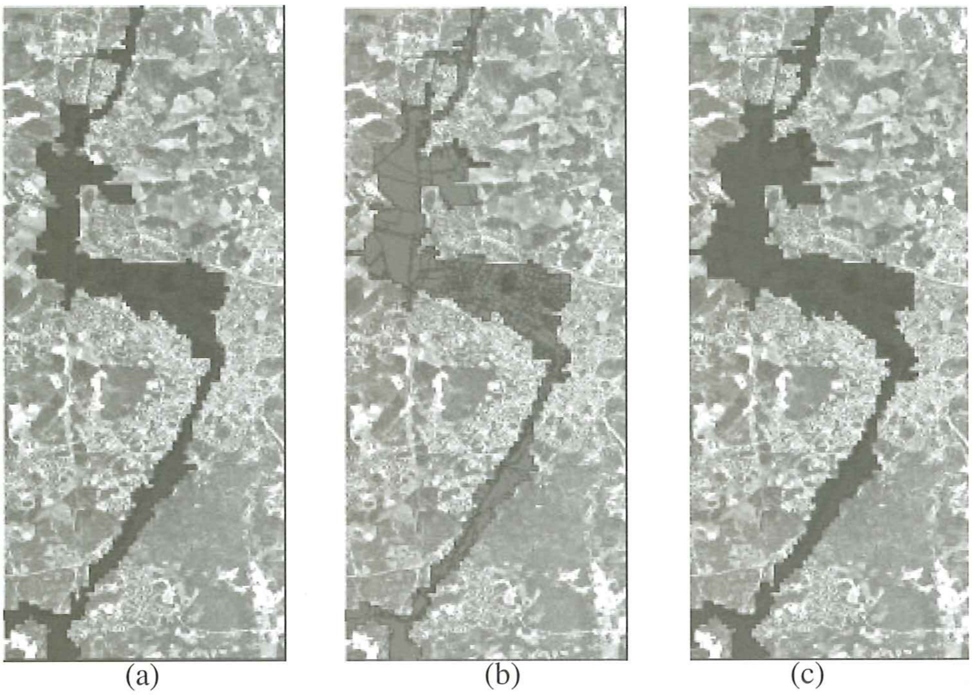

Figure 7. Comparisons of affected areas with different Manning's resistance numbers, where a is the result using *a* Manning's number of 33, *b* 10, and *c* 5. The background is an aerial photograph of the study area.

environment.

When using the MIKE21 model, a dimensionless flow parameter comes into play called the Courant number, defined as $C = c(\Delta t/\Delta x)$ where Δt is the time step, Δx is the grid spacing, and c is the celerity, defined by $c = \text{sqrt}(g\times h)$ 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 modeling flow, the Courant number should be kept under 5 (in general). For a cell size of 100 ($\Delta x = 100$ metres), the constraint on Δt 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 modeling 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 factors used in emergency management planning. DHI Water & Environment is currently researching methods to address this area.

VI. CONCLUSIONS AND FURTHER DIRECTIONS

This study has developed an integrated approach to obtain flood inundation and risk information for flood emergency planning for a community using geographic information systems (GIS) and hydrodynamic modeling (MIKE21). A GIS using the ESRI suite of software running on a Windows NT platform was interfaced to DHI Water & Environment's MIKE21 two-dimensional hydrodynamic flow model. DEM data were obtained and corrected for the study area, manipulated in the GIS, and translated into the MIKE21 modeling environment. Different scenarios were evaluated, and the results were translated back into the GIS for visualization and analysis of a flood event. The system is efficient in estimating the inundation area of a given flood event (e.g. a 100-year flood) and the properties subject to flood and their associated values.

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 modeling activities. Preparation of Bathymetry input for MIKE21 would take up to hours, or days if the XYZ file is to be prepared, depending on the user's experience. With the automated processing, it only takes about 5 minutes for such a task, so the time salving 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.

There were no real means to calibrate the simulations. Usually when flood events occur, flow and stage data are rarely recorded. In this study, comparisons have been made between the model outputs from MIKE21 and that from MIKE11 that was operated separately by Swedish Meteorological and

Hydrological Institute (SMHI) on the same river. The model settings used in both models are similar except these otherwise not applicable. The comparison shows that the results have good agreement between each other, particularly in flood water depth and the general shape of flooded area. But MIKE21 seems over-estimate the flood area, particularly in the low part of the floodplain area. Within the working area, the estimated flooded area by Mike11 is about 11.8 km^2, and 12.9 km^2 by Mike21 with a relative difference of 8.5%. However, in the low part of river Mike21 estimated inundation area is about twice as large as Mike11. One explanation is that we have not set up the dams and floodgates controls in MIKE21 with the assumption that they would be fully open in a flood event, nor the tilt system, thus the flood goes without constraint. This can also be explained by the nature and the underpinning algorithms in the 2D and 1D modeling techniques (details see DHI User Manual). However, we have tried to implement the best available modeling and GIS technology available to us, tempered of course by cost and resources. The modeling methods described in this study appear to give us a reasonable description of what may occur in designed flood scenarios (e.g. 100-year floods), and we will be applying this technology toward future emergency management planning endeavours. In the future, remote sensing techniques (radar and optical), whenever applicable, should be utilized for real-time validation and calibration in a flood events.

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 take to carefully choose all these factors, sometime prioritize them, so that both accuracy and stability can be achieved. In fact, this is a common recognized problem, and the DHI Water & Environment is now dealing with this problem ('Blow-up') and the improved version will become available soon (Karsson, DHI Göteborg, personal communication, 2001). Anyway, to run the model correctly, one must have some understanding of the hydrologic methods used in the model, which helps to correctly set up the model inputs and parameters.

Most of the GIS data sets used in this study are adequate with acceptable accuracy. The key data sets used are DEM, property and river network. Among these, the DEM is the most important factor in the hydrodynamic modeling. The current DEM has 1 m vertical resolution that is too coarse for such a modeling activity, a finer DEM (e.g. up to 0.1 m vertical resolution) would greatly improve the model quality. Furthermore, a low resolution DEM often does not contain detailed linear information such as embankments, roads, fences or tilts which either raise or depress the flood plain. Using a finer DEM allows these be incorporated into the DEM. Nevertheless, the vertical resolution seems more important than the horizontal resolution in the hydrodynamic modeling.

It was clear from the results that a two-dimensional flow simulator was required to adequately describe the flow. MIKE21 seemed to function adequately once the appropriate set up was honored. A one-dimensional model would not have been able to model these scenarios properly. The C++ Translators between MIKE21 and ARC/INFO developed in this study worked very well. ARC/INFO GRID, ARCEDIT and Arc/View Spatial and 3D Analyst were the main GIS components used.

In our further studies, more precise hydrologic variables are to be specified which best represent the reality. More accurate DEM data are to be acquired and used in the hydrodynamic modeling. More automated procedures on data processing and integration are to be developed and a user-friendly flood decision support system (FDSS) is to be developed for the emergency planning. We have already previously developed an integrated drainage network analysis system (IDNAS) (Yang *et al.*, 2000a [9] and 2000b [10]). Such system simulates the water flows in a constrained channel network system. Our immediate further work will start with the integration of such a 1D channel network flow system with a 2D overland flow model that would enable the dynamical simulation and visualization 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.

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