

RESOLUTION ISSUES OF ELEVATION DATA DURING INUNDATION MODELING OF RIVER FLOODS

S. ANDERS BRANDT

Senior lecturer, Division of Geomatics, Department of Technology and Built Environment,
and Gävle GIS Institute, University of Gävle, SE-801 76 Gävle, Sweden
(Tel: +46-26-648500, Fax +46-26-648828, e-mail: sab@hig.se)

Abstract

A case study of the Eskilstuna River in Sweden is presented. This study is carried out within the project KRIS-GIS[®], a Swedish initiative of handling crisis situations, including flooding. The purpose is to show how different resolutions in input elevation data affect the resulting inundation maps. Terrain elevation points at the sides of the river were gathered from an airborne laser altimetry survey, and river bed elevations were gathered from an echosounding survey. The terrain model was constructed in ArcView GIS as a triangulated irregular network (TIN), which served as the base for all later modeling. The hydraulic modeling was done as one-dimensional steady flow in HEC-RAS flow routing software. High-resolution elevation data resulted in better inundation delineation than did low-resolution elevation data. If the mean water discharge was used in the modeling and if the river is narrow, a low resolution could even lead to that the river itself would not be marked as inundated. At high water discharges, the river was usually inundated, but there was great uncertainty if the riparian areas really would be flooded or not. With steep side slopes, the delineation of inundation becomes more certain, while at gentler side slopes, the flow is distributed on a larger surface with a risk that the raster cells will be incorrectly marked regarding inundation. Finally, the use of high-resolution elevation data compared with low-resolution data, makes estimates of friction factor, Manning's n , relatively more important for correct results in inundation studies.

Keywords: Digital elevation models; Scale; Floods; Inundation; GIS; HEC-RAS; Hydraulic modeling; Airborne laser altimetry

1. INTRODUCTION

During the last decade, many countries have suffered from severe river floods. Meanwhile, politicians, public authorities, organizations, etc. have realized that river flooding is not some improbable event, only happening to others. Also, a global climate change is expected to occur which may further increase the frequency and magnitudes of heavy storm events. Therefore, it is not a question of if rivers will be flooded, it is question of when and how much. This puts a big responsibility on e.g. physical planners, to make sure that new areas are not planned at places which may be flooded, or that already existing areas can be managed to minimize the effects of floods.

One way to be better prepared for river flooding events is to produce inundation maps of different flood magnitudes, which can be used either when storm events are expected, or for use in physical planning. In this paper a case study of the Eskilstuna River in Sweden is presented. This study, as well as an earlier study of river flooding in Eskilstuna, is carried out within the project KRIS-GIS[®], a Swedish initiative of handling crisis situations, including flooding. The earlier flooding study by Yang et al. (2001, 2002) and Yang and Rystedt (2002) used MIKE 21 as hydraulic modeling software. Their main contribution was the programs for converting data and results between MIKE 21, ARC/INFO GIS and ArcView GIS, but also the issues of flood impact on real estate were studied and discussed. Some earlier modeling on Swedish rivers by the Swedish Meteorological and Hydrological Institute (SMHI, 2001), have also been done, but these results have been criticized for being too uncertain, because the inundation maps are based on elevation models of 2500 m² (50×50 m) grid-cell sizes. The purpose now is to show how different resolutions in input elevation data affect the resulting inundation maps. The studied area covers the river and surroundings from the lake Hjälmaren to the outlet in lake Mälaren. The river reach is about 22 km long and flows through a densely populated district with its main city Eskilstuna (Fig. 1).

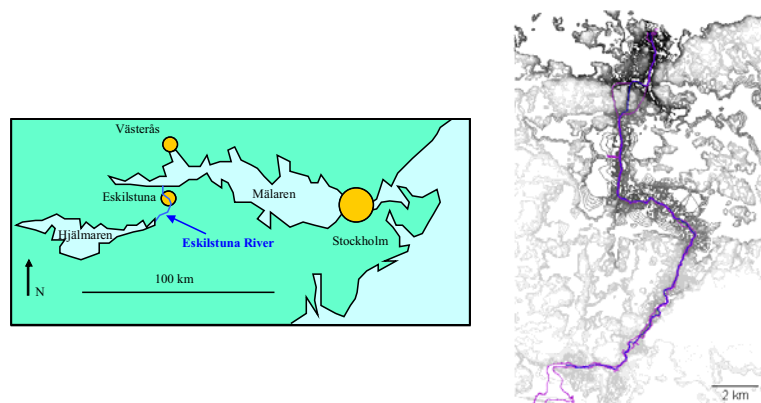


Fig. 1 The Eskilstuna River (left) and the studied reach (right). Flow is to the North.

2. MATERIAL AND METHODS

The success of inundation modeling mainly depends on the quality of correct terrain representation. For this study an airborne laser scanner survey had been conducted by TopEye AB. The survey was conducted along the river shores of the river during the 13 April, 2004, on 300 m altitude, generating 41 million data points, i.e. approximately 2 points per square meter. These points were filtered by TopEye AB down to 4.6 million points, so the data could be practically handled. The filtering aimed at trying to preserve the terrain undulation, and only removing points that have no influence on final terrain modeling. The data is supposed to have an accuracy of better than 0.5 m horizontally, and better than 0.15 m vertically. To get a representation of the river bed, an echo-sounding survey was conducted by Myrica AB, 14-16 June, 2004. 12127 points were echo sounded and positioned with a GPS.

The laser and echo-sounding data sets were combined with nodes from the Swedish National Land Survey's (Lantmäteriet) 5 m contour-interval elevation curves to produce a terrain model covering not only the areas close to the river, but also the surrounding terrain (Fig. 2). The model was constructed in ArcView GIS as a triangulated irregular network (TIN), which serves as the base for all later modeling.

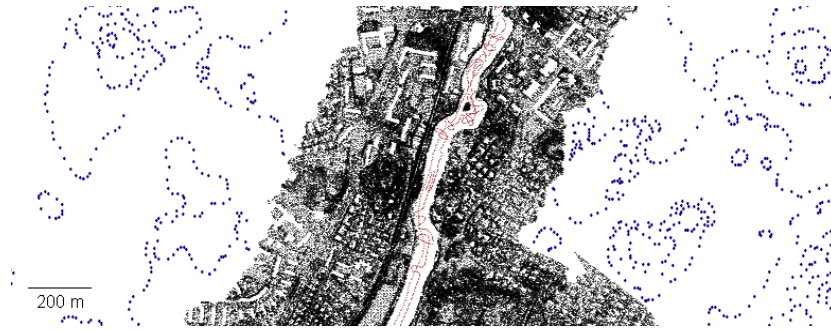


Fig. 2 The terrain model is built from sparsely distributed points from contour curves (5 m equidistance), densely distributed laser scanned points, and echo-sounded points.

The hydraulic modeling was done as one-dimensional steady flow in HEC-RAS flow routing software (Hydrologic Engineering Center, 2002b). There may be a risk that steady flow underpredicts the resulting water surface if the flood wave is of short duration. Here, however, this is not a main concern. The HEC-RAS model has also been shown to perform well in competition with more sophisticated 2D models (Horrit & Bates, 2002). The input to the model was four different water discharges: $23.7 \text{ m}^3 \text{ s}^{-1}$ is the mean water discharge, $70 \text{ m}^3 \text{ s}^{-1}$ is the annual flood, $123 \text{ m}^3 \text{ s}^{-1}$ is the 100-year flood, and $198 \text{ m}^3 \text{ s}^{-1}$ is the calculated highest flow possible (not related to any frequency). These discharge values have been calculated by SMHI (2001). The HEC-RAS model also needs cross-section elevations to be able to calculate the downstream movement of flow. The cross sections were derived from the terrain TIN, as well as some additional data, e.g. stream lengths between sections, etc. The cross-section information was exported from ArcView using the HEC-GeoRAS extension (Hydrologic Engineering Center, 2002a). Also, different values of ground friction, Manning's n , were tried.

After running the HEC-RAS model for different water discharges, the resulting water-surface elevations for all cross sections were imported back to ArcView. First a polygon was created that covered the area containing all cross sections. Then the polygon was rasterized and assigned elevation values from interpolation of the cross sections' water surface elevations. A raster covering the same area was created by interpolating the terrain TIN. Several resolutions of the rasters were tried. Finally, these rasters were compared with each other, cell by cell. If a water surface cell was above the terrain surface cell, the cell was marked as inundated and attributed with the inundation depth, and similarly, if the water cell was below the terrain cell, the cell was marked as not inundated (see Hydrologic Engineering Center, 2002a). Inundated areas were calculated for the four different water discharges as well as for different resolutions of the rasters. Also see Tate et al. (2002) for comprehensive

descriptions on the methods when using ArcView and HEC-RAS. Finally, visualization attempts of flooded areas were made.

3. RESULTS

The results of the hydraulic modeling and following inundation analysis can be seen in Figs 3 to 10. In Fig. 3, four simulated water discharges are shown for the whole reach between the lakes Hjälmaren and Mälaren.

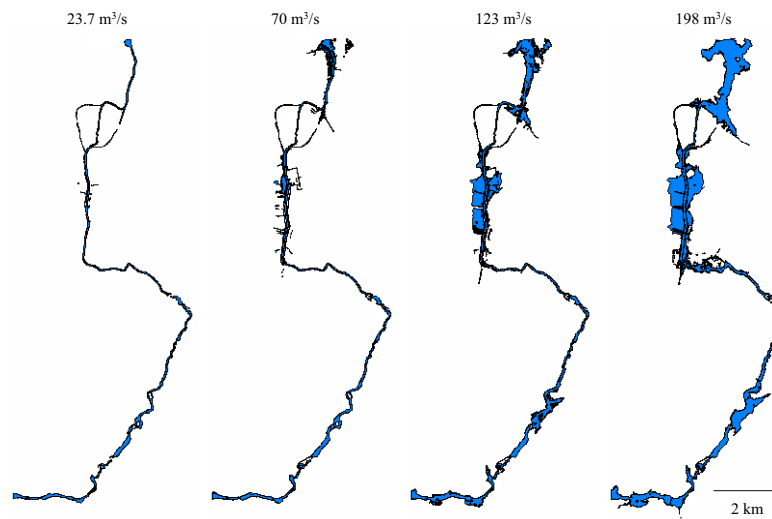


Fig. 3 Four different inundation scenarios. $23.7 \text{ m}^3 \text{ s}^{-1}$ is mean water discharge, $70 \text{ m}^3 \text{ s}^{-1}$ is annual flood, $123 \text{ m}^3 \text{ s}^{-1}$ is 100-year flood, and $198 \text{ m}^3 \text{ s}^{-1}$ is maximum probable flood.

If the high-resolution terrain model is used as base, but rasterized to different resolutions, the final results will be poorer. Fig. 4 shows how different resolutions for the mean water discharge, $23.7 \text{ m}^3 \text{ s}^{-1}$, affect the results in the analysis, and correspondingly, Fig. 5 shows the maximum possible water discharge for different resolutions.

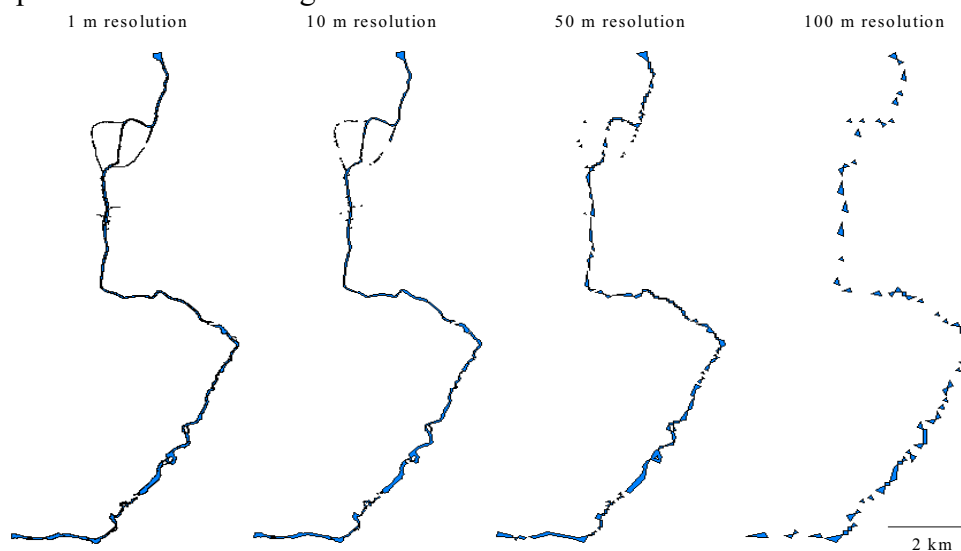


Fig. 4 Mean water discharge, $23.7 \text{ m}^3 \text{ s}^{-1}$, used with four different resolutions.

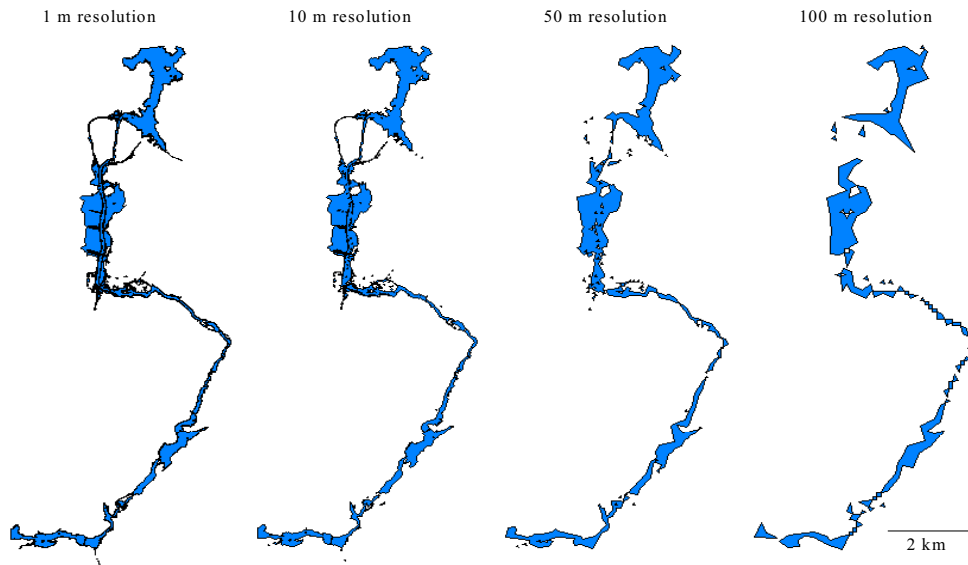


Fig. 5 Maximum probable water discharge, $198 \text{ m}^3 \text{ s}^{-1}$, used with four different resolutions.

To better illustrate the effects of different resolutions, two areas are looked into detail. Fig. 6 shows an area with steep river valley sides and Fig. 7 shows an area with gentle cross-sectional slopes. Both are shown with maximum probable flow and as overlays on air photos for reference.

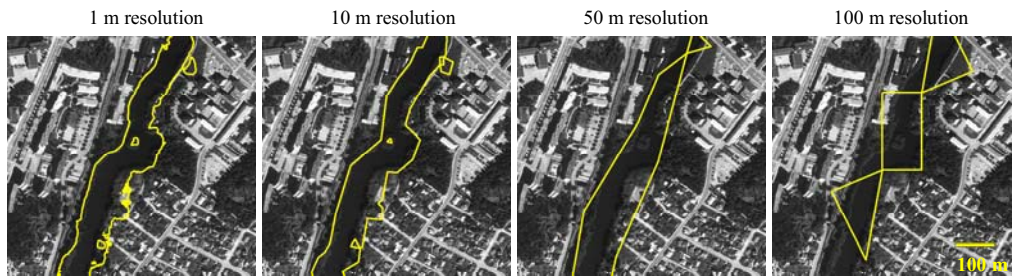


Fig. 6 Maximum probable water discharge, $198 \text{ m}^3 \text{ s}^{-1}$, used with four different resolutions at an area with steep cross-sectional slopes (Southeast part of Eskilstuna River). Permission for distribution of air photos approved by National Land Survey of Sweden March 21, 2005.

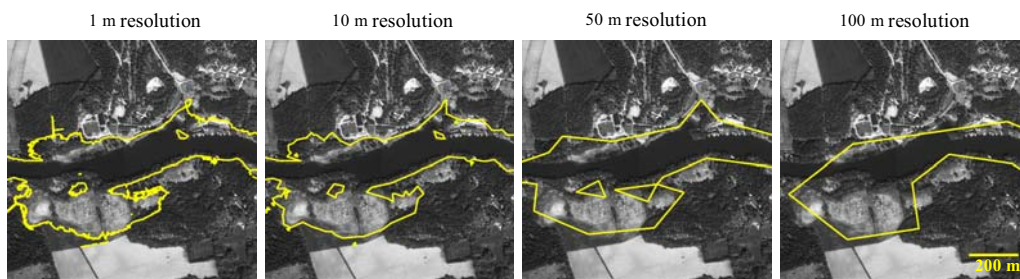


Fig. 7 Maximum probable water discharge, $198 \text{ m}^3 \text{ s}^{-1}$, used with four different resolutions at an area with gentle cross-sectional slopes (South part of Eskilstuna River). Permission for distribution of air photos approved by National Land Survey of Sweden March 21, 2005.

The effect of changed resolution, as can be seen in Figs 6 and 7, is proportional to the change of resolution. When a poorer elevation model is used as base for the analyses, the results will be even poorer, and only useful for general planning. To illustrate this for the maximum probable flow, analyses based on the high-resolution ground data was compared with analyses based on the National Land Survey's ground data of 50 m × 50 m cells (see Fig. 8).

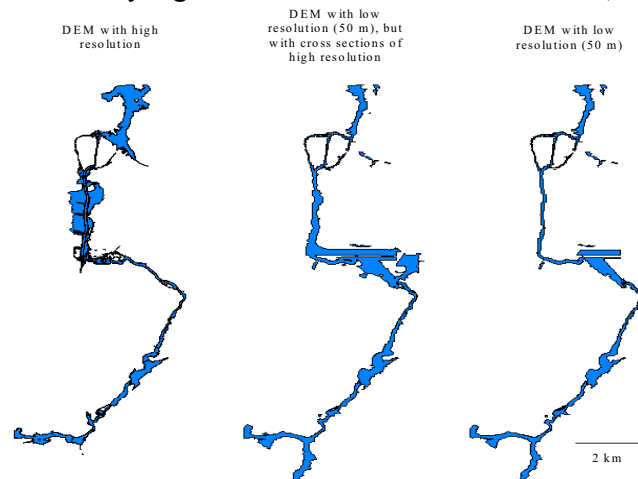


Fig. 8 Maximum probable water discharge, $198 \text{ m}^3 \text{ s}^{-1}$, overlain on terrain models of different quality. High-resolution scanned data (left, same as left in Fig. 5) compared with two alternatives of 50 m ground resolution: 50 m and high-resolution cross sections (middle) and 50 m resolution, only (right).

Besides the resolution of the elevation models, the ground friction, i.e. Manning's n , influences the analyses. Fig. 9 shows the flooded areas with values of Manning's n of 0.033, 0.100, 0.200 and a combination where $n = 0.033$ in the river and $n = 0.100$ in areas beside the river. A value of 0.1 corresponds to a flow over ground covered with bushes.

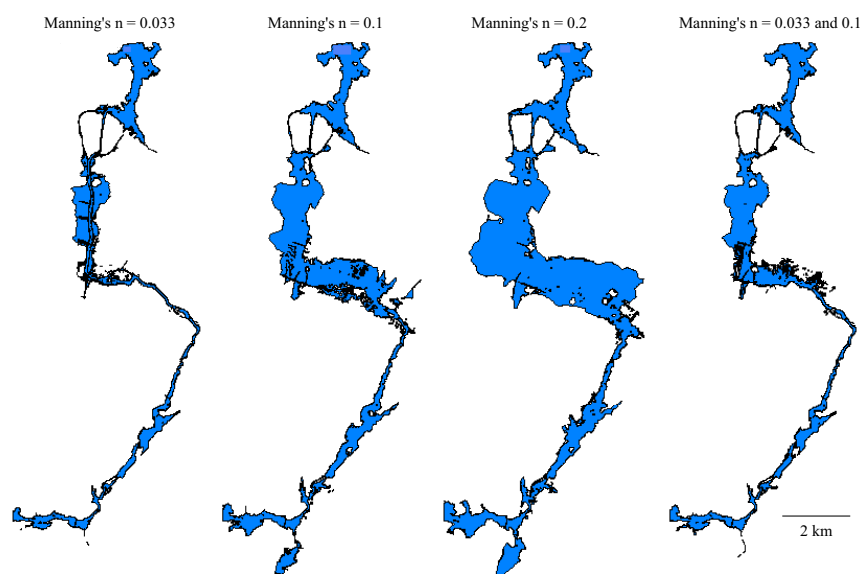


Fig. 9 Flooded areas for different values of Manning's n at maximum probable flow.

Finally, an area close to the flooded margin is visualized (Fig. 10). The image consists only of the original terrain TIN overlain with an air photo and the flood polygon.

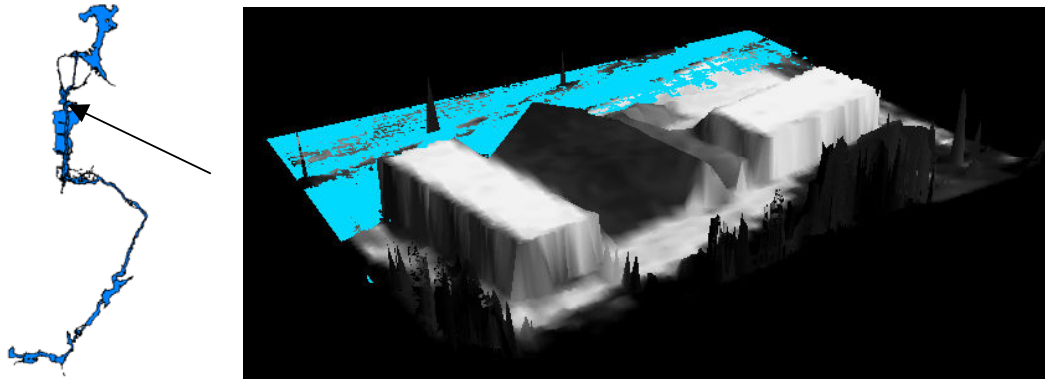


Fig. 10 Visualization of the flood margin together with the original terrain TIN. Even though no image manipulation has been made, houses and trees are clearly visible.

4. DISCUSSION

Not surprisingly, using high-resolution elevation data leads to better inundation results than do low-resolution elevation data. If the mean water discharge is used and if the river is narrow, a low resolution may even lead to that the river itself will not be marked as inundated. At high water discharges, the river is usually marked as inundated, but there is great uncertainty if the riparian areas really will be flooded or not. Note that the hydraulic modeling for the areas in Figs 4 and 5, all are based on the high-resolution data. Only for delineating inundated areas the resolution has been changed. Hence, the lower resolution gives poorer results of expected magnitudes. If the result from the hydraulic modeling is overlain on a low-quality terrain model, as in Fig. 8, the inundated areas are very different to those of a high-resolution terrain model. It will not help much if the results are presented with high resolution, since the delineation of inundated areas is not based on high resolution data. The results from the low-resolution ground data resembles the results of SMHI (2001) and Yang et al. (2001), who had 50 m as best ground resolution.

There are some differences between river cross sections with steep slopes and cross sections with gentle slopes (Figs. 6 and 7). With steep side slopes, the delineation of inundation becomes more certain. Then the cell resolution determines the uncertainty. At gentler side slopes, the flow is distributed on a larger surface, which increases the need of high-resolution elevation data. A large raster cell, still only has one elevation value, and if the water surface is close to that elevation, which probably is the case, there is a big risk that the raster cell will be incorrectly marked regarding inundation.

The influence of the quality of river bottom elevations is not as severe as the influence of the quality of the ground elevations. Since this is a study of high-flow events, the parts of river cross sections occupied by the mean water discharge are very small, in this case a cross-sectional area with about 1/8 of the maximum probable flow. Therefore, most energy and

efforts should be spent on acquiring as good elevation data as possible. However, if the normal flow levels are the important one, then high-resolution river bottom data are needed.

How good resolution is needed? That obviously depends on the purpose. If an area is going to be surveyed by e.g. a national land survey, the purpose is probably to support the general public with high quality data for a number of years. Then, airborne laser scanning probably is very cost effective. All users can benefit from them. If a public authority is making general plans for an area, existing low-resolution data, from e.g. contour curves, may be sufficient. But if detailed plans are prepared, where individual houses may be possible to pin-point, high-resolution data are needed. This is also necessary in areas where building of new houses are expected. Similarly, the high-resolution data will aid the planning for crisis situations in already built-up areas.

The results clearly improve from better resolution of elevation data. Earlier, the quality of this data determined the success of the results. Now, however, determination of Manning's n may be the most important parameter in the analyses to receive reliable results. Most important are correct estimates of Manning's n in flat areas, where the wet perimeter are long relative to the cross-sectional area of flow (Fig. 9).

The final decisions that have to be made are which water discharges should be used in the hydraulic modeling and which software should be used. Today, many flood risk estimates are based on e.g. the 100-year flood. This sounds good and intuitive, but is it? The 100-year flood has probably been calculated from only a few years of data, but changes in climate can be even more influential. A 100-year flood today, can be a 10-year event in a near future. If this happens, either we have to hope there have been planners who have not utilized areas too close to the rivers, or that the use of high-resolution data can aid crisis planning and by that minimize the effects of floods. The modeling software used, probably depends on the individual hydrologists and hydraulic engineers. If the river has a well defined valley to flow in, one-dimensional models are sufficient for most cases. In this study, therefore, there may be some uncertainties in the area where the flow divides into three branches just south of the outlet in lake Mälaren. If large flat areas exist, then two-dimensional models should be considered.

Having reliable results that can be needed in e.g. crisis situations, does not mean that the results are commonly used. Therefore, it is of great importance that visually attractive images can be produced, that enhances the importance of the results. Thanks to the laser scanned data, relatively realistic 3D models can be shown directly and e.g. the flooded areas around a specific house can be interpreted (Fig. 10).

5. CONCLUSIONS

Several different flooding scenarios have been modeled and results have been exported to a GIS and mapped as inundation areas based on different ground elevation resolution. The better the ground resolution, the better and more exactly the inundated areas can be determined. It is also shown that by using lower-resolution ground-elevation data, the

resulting inundated areas will differ so much, that usage of the results is affected. E.g., incorporation of accurate flooded areas in detailed physical planning will be limited.

To model small narrow rivers, using high-resolution data is necessary. Otherwise, the river may be totally invisible in the results. For larger wider rivers, high-resolution data may not seem to be necessary, but if delineation of the flooded areas needs to be correct, high-resolution is needed. If high-resolution data are used, then determination of Manning's n will be the limiting factor for correct inundation results. Therefore, differentiation of n depending on landuse is of importance.

A weakness in inundation modeling is to know which water discharge to use. For example, should statistical data be used, such as the 100-year flood? Should a maximum probable flow be used, or are there any other factors that need to be considered?

ACKNOWLEDGEMENTS

This study had not been possible without financial support and data delivered via the project KRIS-GIS[®], handled by the National Land Survey of Sweden.

REFERENCES

- Horrit, M.S., Bates, P.D., 2002. Evaluation of 1D and 2D numerical models for predicting river flood inundation. *J. Hydrology*, vol. 268, pp. 87-99.
- Hydrologic Engineering Center, 2002a. HEC-GeoRAS: An Extension for Support of HEC-RAS using ArcView. User's Manual, Version 3.1. US Army Corps of Engineers, Davis, ix+114 p.
- Hydrologic Engineering Center, 2002b. HEC-RAS: River Analysis System. User's Manual, Version 3.1. US Army Corps of Engineers, Davis, ix+462 p.
- SMHI, 2001. Översiktlig översvämningsskartering längs Svartån - Hjälmarens - Eskilstunaån: sträckan från sjön Toften till Mälaren. Räddningsverket Rapport 18, 12 p. + appendices.
- Tate, E.C., Maidment, D.R., Olivera, F., Anderson, D.J., 2002. Creating a terrain model for floodplain mapping. *J. Hydrologic Engineering*, vol. March/April, pp. 100-108.
- Yang, X., Grönlund, A., Tanzilli, S., 2001. Predicting Flood Inundation and Risk Using Geographic Information System and Hydrodynamic Model: A Technical Report on the Case Study at Eskilstuna. Gävle GIS Institute, 34 p.
- Yang, X., Rystedt, B., 2002. Predicting flood inundation and risk using GIS and hydrodynamic model: a case study at Eskilstuna, Sweden. *Indian Cartographer*, vol. 22, pp. 183-191.
- Yang, X., Grönlund, A., Tanzilli, S., 2002. Predicting flood inundation and risk using geographic information system and hydrodynamic model. *Geographic Information Sciences*, vol. 8(1), pp. 48-57.