Title: Importance of river bank and floodplain slopes on the accuracy of flood inundation mapping

Authors: S. Anders Brandt and Nancy J. Lim

Conference: River Flow 2012: International Conference on Fluvial Hydraulics, San José, Costa Rica, 5-7 September 2012.

Publisher: CRC Press/Balkema (Taylor & Francis Group)

ISBN: 978-0-415-62129-8

Importance of river bank and floodplain slopes on the accuracy of flood inundation mapping

S.A. Brandt & N.J. Lim

Department of Industrial Development, IT and Land Management, University of Gävle, SE-80176 Gävle, Sweden

ABSTRACT: Effective flood assessment and management depend on accurate models of flood events, which in turn are strongly affected by the quality of digital elevation models (DEMs). In this study, HEC-RAS was used to route one specific water discharge through the main channel of the Eskilstuna River, Sweden. DEMs with various resolutions and accuracies were used to model the inundation. The results showed a strong positive relationship between the quality of the DEM and the extent of the inundation. However, even DEMs with the highest resolution produced inaccuracies. In another case study, the Testebo River, the model settings could be calibrated, thanks to a surveyed old inundation event. However, even with the calibration efforts, the resulting inundation extents showed varying degrees of deviation from the surveyed flood boundaries. Therefore, it becomes clear that not only does the resolution of the DEM impact the quality of the results; also, the floodplain slope perpendicular to the river flow will impact the modelling accuracy. Flatter areas exhibited the greatest predictive uncertainties regardless of the DEM's resolution. For perfectly flat areas, uncertainty becomes infinite.

1 INTRODUCTION

1.1 *Background*

It is widely recognised that the resolution of Digital Elevation Models (DEM) affects both the quality and reliability of the results produced by inundation modelling. It is believed to be directly proportional to the ability to delineate the study area and the quality of flood extent results.

The DEMs basically represent the terrain and floodplain morphology, including river bathymetry, which form the basis of any hydraulic modelling. Terrain models with higher resolution are characterized with greater accuracy and precision that in turn provide better stream geometries relevant for modelling overland flows and enabling better hydraulic analyses of the channel (Mason et al. 2003).

With the development of new techniques such as lidar, which enables generation of high resolution DEMs, and with the increasing availability and accessibility to hydrologic data such as river discharges, inundation studies are getting more common, producing better outputs compared with low resolution topographic data. The positive outcome of high resolution elevation models in the form of laser-scanned data, particularly when complemented with bathymetric data, have been regarded in different studies to produce good inundation extents, as compared with lower quality terrain data (Brandt 2005, 2009, Casas et al. 2006, Schumann et al. 2007).

Yet, parallel to the dramatic increase in possible resolution of the elevation models is the expectation to acquire more reliable and accurate results – usually up to an order of magnitude. So far, however, many modellers ignore or are unaware of the inaccuracies that the produced inundation maps still suffer from and the uncertainty of river flood inundation mapping is an often overlooked part of flood risk management and assessment. The correctness of these maps will always remain subjective; e.g. the producers may disregard additional ambiguities immanent in the outputs, unless there is a validation data set that can serve as basis for comparison; or the users may not have the technical knowledge to be able to judge the correctness and uncertainties. The presence of validation data may be relevant in the assessment of model performance in terms of the inundation maps produced. It may also be conducive in calibrating model settings to match its flood boundaries prior to using these parameters for later simulations on more extreme conditions.

A few studies have been carried out where the DEM quality is related to the predictability of the models (e.g. Omer et al. 2003, Raber et al. 2007, Brandt 2009, Cook & Merwade 2009), but still, the issue persists in determining as to how close a modeller can get to attain a realistic inundation extent while using high resolution data, with or without the presence of reference data. With the main focus on the quality of the DEM, this paper will compare the results from two previous studies conducted over Eskilstuna and Testebo Rivers, Sweden, to show ambiguities in the flood maps produced.

1.2 *Aims*

The general scope of this paper is to enhance the knowledge of the inherent inaccuracies flood risk maps possess. The aim of the paper is to answer the following specific research questions:

- By comparing results based on DEMs with varying resolution, how does the uncertainty of flood inundation extent change?
- By comparing results based on high resolution DEMs with validation data, which conclusions can be drawn about the uncertainty?

1.3 *Study Areas*

For this project, two rivers in central Sweden have been studied. The Eskilstuna River, with an average flow of 24 m^3/s, is flowing to the north from lake Hjälmaren to lake Mälaren through the city Eskilstuna, located about 90 km west of Stockholm. Two areas were studied in detail. One relatively flat, with 1731 m river length surrounded by agricultural areas and shrubs, just northeast of lake Hjälmaren, and a 2241 m long stretch with relatively steep side slopes in the southeast parts of the Eskilsuna city centre.

The entire Testebo River stretches 85 km long from northwest of Ockelbo to its drainage in Gävle. For this study, however, the 7 km part of the channel from Åbyggeby to Oskarsbron in Strömsbro, which is situated just north Gävle City (about 160 km north of Stockholm) was investigated. The northern part of the study area is surrounded by coniferous forests and the channel's banks are characterised with steeper slopes. The central portion, particularly in Varva and Forsby, is flat and is composed mainly of pasture land, although built-up areas border the floodplains. The river's average flow is 12.1 m^3/s.

2 MATERIAL AND METHOD

2.1 *Topographic data*

The ground data for the Eskilstuna River was gathered through laser scanning by TopEye AB in 2004. On average, there were 1.64 and 1.36 points/m^2, corresponding to cell sizes of 0.78 and 0.86 m, in the two areas, respectively. The two datasets were later degenerated by Klang & Klang (2009). Several DEMs down to 50 m cell size resolution were produced by removing random ground points and by introducing, in both x/y and z directions, random errors of magnitude 1 σ, as well as systematic errors of $0.5*\sigma$ for some DEMs (see Brandt 2009 and Klang & Klang 2009 for details). The bathymetric data, collected by Myrica AB, were then added and a TIN could be created.

The elevation data used for the Testebo River consisted of both the 50 m cell size resolution dataset of the Swedish National Land Survey and by laser-scanned data acquired in 2008 by SWECO, consisting of 4 million model (filtered) key points, with point spacing between 0.20 to 1.80 m. The latter's data accuracy is believed to be about 0.10 m horizontally and vertically. The channel elevation was comprised mainly of echo-sounded data with 30,000 points. This was supplemented with interpolated bottom elevation points in the shallow parts of the stream that were not possible to be surveyed with echo-sounding (Lim, 2009). The data were then combined into TIN models, which constituted the primary topographic data for the hydraulic modelling.

2.2 *Hydraulic Simulation*

The flood simulation was modelled with the one-dimensional (1D) model HEC-RAS (Hydrologic Engineering Center 2008) using steady-flow and mixed-flow regime settings. Despite the limitations attributed to 1D models, results produced by them, especially when used with high resolution data, are comparable to the results derived from the more complex two-dimensional flood models (Horritt and Bates 2002, Lim 2011).

Channel and floodplain geometries, such as cross-sections, streams, flow paths, banks and land use, which were assigned with Manning's n friction coefficients, were created in ArcGIS with the help of the HEC-GeoRAS extension. These GIS themes were then imported in HEC-RAS, where the actual hydraulic simulations were performed.

Before the simulation, cross-sections were filtered to a maximum of 500 elevation points, which is what can be handled by the software. Particularly for models generated from laser-scanned data, this is an often undertaken step because of the fine geometric details of the models. However, tests by Brandt (2009) have shown that such filtering has only a very limited impact on the final flood prediction results.

The discharge rate utilised for the Eskilstuna River was 198 m^3/s, which, according to the Swedish Meteorological and Hydrological Institute, is the maximum possible flow that can occur in this river. The lower boundary conditions for the two reaches in the Eskilstuna River were assigned to known water surface elevations. For the Testebo River, a flow rate of 160 m^3/s was used. This is equivalent to the flood that occurred in 1977 and also corresponds to the 100-year flow. Lower boundary condition applied was based on the actual water surface elevation (i.e. 14.34 m) measured in Oskarsbron during the 1977 flooding.

2.3 *Validation data*

No data of extreme flows exist for the Eskilstuna River. Instead, the modelled extent resulting from the original high resolution DEM was used as the reference data. All comparisons were then made to the DEMs including artificial errors.

Validation data for the Testebo River was provided by Gävle municipality. This reference inundation extent was based on an aerial photograph of the flooding that occurred on 12 May 1977. The flow was recorded to have a discharge of 160 m^3/s.

2.4 *Computation of river side slope and disparity distance*

For both the left and right overbanks of each cross-section, points were extracted from the border of the reference flood, as well as from the border produced by the hydraulic modelling, and the distance separating the two boundaries were measured. The average side slope between the two border points were also computed, before comparing its effect to the disparity between the validation and the simulated data.

3 RESULTS

3.1 *Eskilstuna River*

Several factors were looked into detail for the Eskilstuna River. One of these was the comparison of the water surface elevations. The average of the reference's and the degenerated models' cross-sections were compared for both reaches, respectively. The flat southern area did not show any significant deviation between the reference and the poorer resolution models. The northern area with steeper side slopes, however, showed an increasing deviation, from 5 cm decrease for the 10 m resolution DEM, to 25 cm decrease for the 50 m resolution DEM. Because of the known water surface elevation used for the lower boundary condition, the water elevation deviation ranged from 0 cm at the lower end to 12 and 45 cm in the upper end for the flat southern and steeper northern areas, respectively.

With respect to the width of the river, a gradual increase in deviation occurred as the models became poorer. The best models showed only about a single meter deviation for the cross-sections' average, but increased to about 10 m for the 25 m resolution DEM, and 20 m and 30 m for the 50 m resolution DEM, for the southern flat and steeper northern areas, respectively. The maximum deviation was almost 150 m for one of the cross-sections in the flat southern area. Whereas the water surface level was not much impacted when systematic errors of the surrounding terrain elevation were introduced, the width was. The average widths changed between 5 to 10 m, depending on the negative or positive systematic error of the surrounding terrain elevation (assuming that river bottom elevations were correctly measured and had no systematic error). A direct consequence of the width variation was that the inundation areas also manifested corresponding proportional percentage difference. Figure 1 shows how much the inundation borderline differs from the reference model.

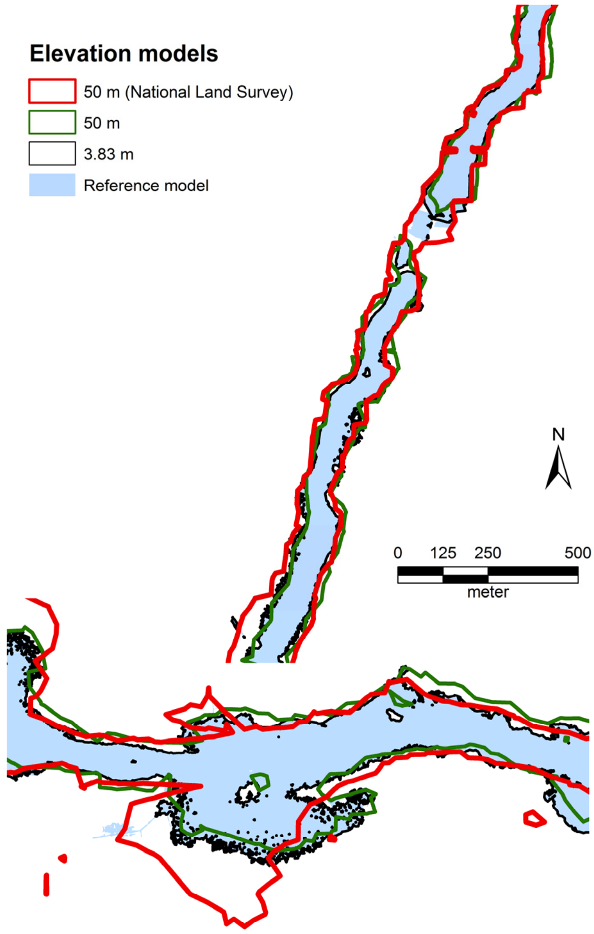

Figure 1. Flood inundation extents for DEMs of different resolution (Eskilstuna River, northern (above) and southern (below) area).

When the disparities of the water boundary location between the different models and the reference model were plotted against the river side slopes, it was evident that regardless of DEM quality, the uncertainty of the boundary location got bigger and bigger as the river side slopes became flatter, and that poorer resolution DEMs further augmented the risk of inaccurate mapping (Figures 2-3).

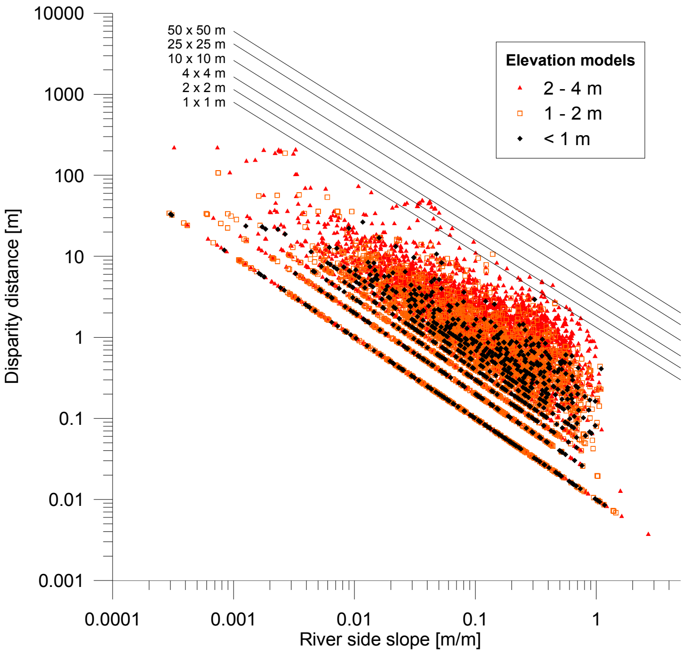

Figure 2. Disparity distances between the degenerated models of relatively high resolution and the reference model plotted against the river side slope (Eskilstuna River).

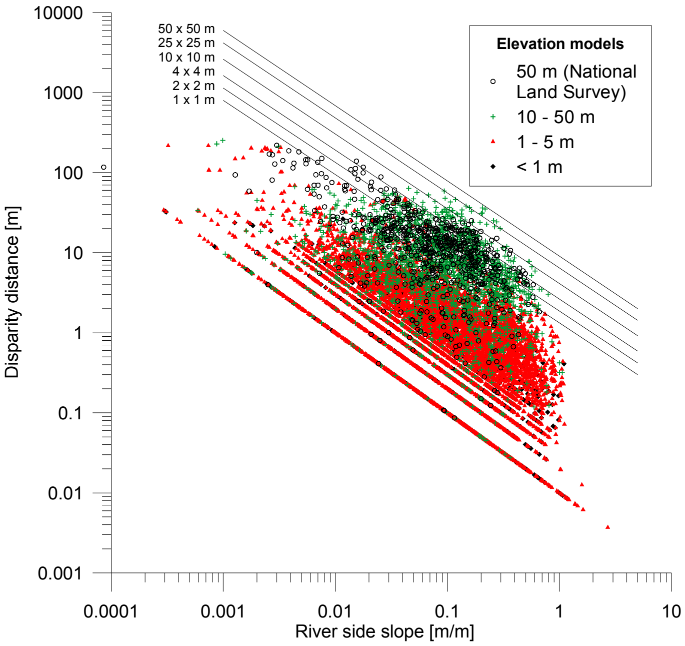

Figure 3. Disparity distances between the degenerated models with different resolutions and the reference model plotted against the river side slope (Eskilstuna River).

In the Figures, envelope curves for different DEM resolution are also given, implying that the curves define the maximum inaccuracy, at least for the investigated areas of Eskilstuna River, for different river side slopes. Note, however, that the inaccuracy never can be smaller than half the cell size.

3.2 *Testebo River*

For the Testebo River, a larger disparity from the validation model was apparent for the low resolution 50 m Swedish National Land Survey dataset, with an average distance of 41 m, compared with about 28 m computed mean for the laser-scanned data. The largest distance difference between the actual flood boundary and the modelled ones was also calculated for the 50 m model (584 m), which was more than 150 m wider than the maximum extent produced by the lidar data. The difference between the modelled inundation and the 1977 event at the location where the largest deviations were measured is shown in Figure 4.

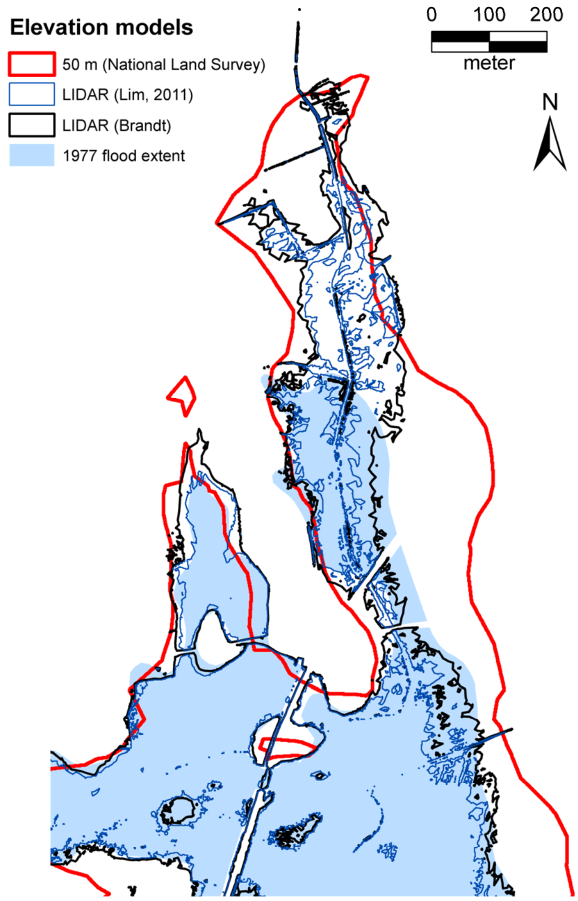

Figure 4. Difference in flood inundation extent for DEMs of different resolution at the central portion of the Testebo River.

The variation of disparity between the validation data and the modelled flood extents increased with flatter slopes (Figure 5), even without taking into account the quality of the topographic data used. Disparities greater than 200 m were concentrated on terrain slopes between 0.002-0.003 m/m, which were specifically located in the flat central floodplain of the study area. Inundation extents between 0 to 50 m from the actual flood data were on average slopes of greater than 0.06 m/m.

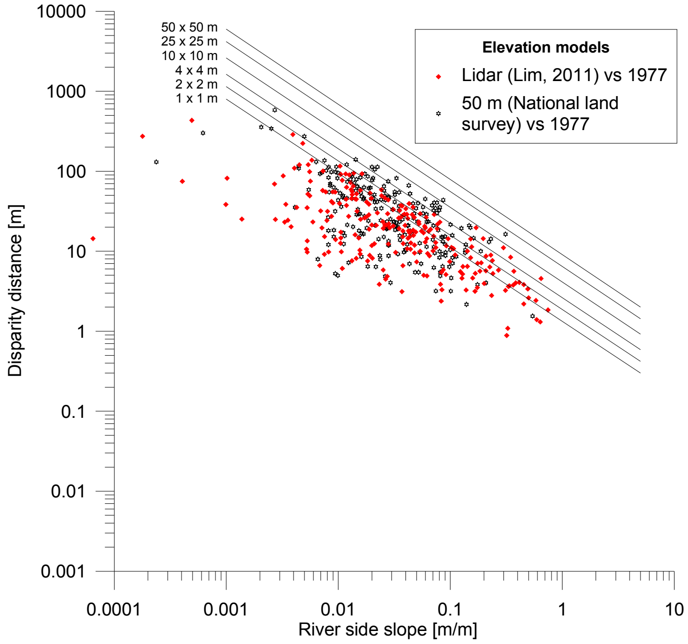

Figure 5. Disparity distances between the modelled inundation and the validation data plotted against the river side slope (Testebo River).

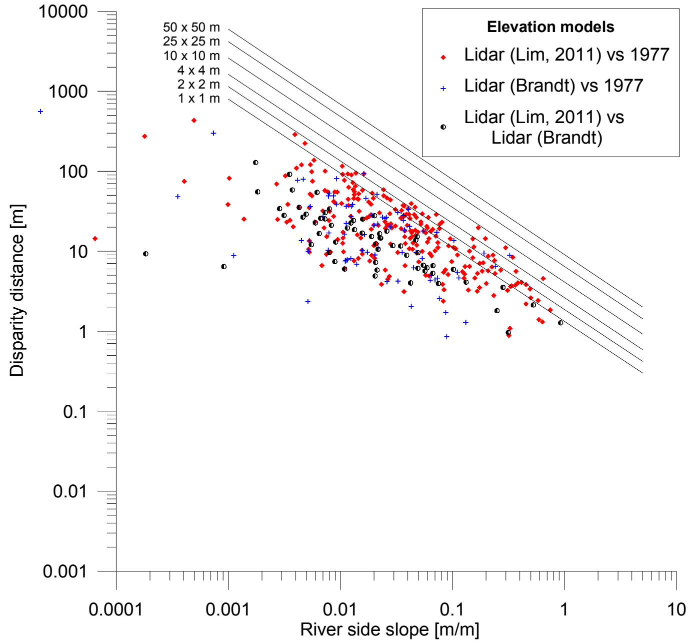

Figure 6. Comparison of disparity distances between models of two different modellers using the same elevation data (Testebo River).

A recent study over the southern part of Testeboån was conducted by Brandt utilising the same high resolution topographic data, but with different cross-sections and boundary conditions applied (reported in Melin et al. 2011). The average distance of the new simulation from the 1977 event's extents was about 29 m, while the maximum disparity measured was almost 560 m. Comparing this to Lim's (2011) study for the laser-scanned data, the mean distance between the two was about 14 m. The largest difference calculated was 128 m, which was measured in the same cross-sectional position that generated all the maximum discrepancy measures for all the models when compared with the validation data (cf. Figure 4).

When the disparities between the high resolution models were plotted in the disparity distance-river side slope diagram, it was evident that both models showed disparities similar to relatively low resolution models, but when compared only with each other and not against the 1977 flood, they appeared to be approximately similar, resembling a high-resolution data pattern (Figure 6).

4 DISCUSSION

The results for high resolution DEMs clearly show that the horizontal disparity between modelled extents and validation data is limited in areas of steeper river side slopes, where the water is confined from overflowing or spilling over the banks. In flatter areas, the disparity between the two becomes greater and the model results thus more uncertain. In floodplains that are characterized by huge flatlands, the ambiguity is greater. Furthermore, for example strong winds can produce unexpected results. In such cases it is virtually impossible to calibrate the model to create a satisfactory match

The slope effect is also visible for lower resolution data, even after recalibrating the model. The unpredictability of the results gradually increases from steep river side slopes to flat side slopes.

A high certainty, using either low or high resolution DEMs can only be guaranteed when the flow is constrained in areas with steep river side slopes and between river banks. Therefore, discharge rates and other factors that control overbank flow also have to be considered. Once the water overflows, the certainty will depend on the topographic characteristic of the floodplain. Hence, what may seem certain for the moment may suddenly result in an unanticipated flood flow pattern.

The opportunity to compare the results from two different rivers and two different modellers also provide some valuable insights. The results from the poorer resolution DEM of Testebo River produced very similar outcomes to those of the Eskilstuna River. The high resolution study of Testebo River, however, demonstrated relatively poor results considering what was derived from the Eskiltuna River study. This can partly be explained by the flaws in the validation data (the 1977 flood). On the other hand, the results from two different modellers utilising different parameters showed greater similarity, reflecting smaller uncertainties, than the results from the validation DEM.

5 CONCLUSIONS

Intrinsic uncertainties possessed by flood risk maps were investigated by relating the disparity distances and the average side slopes between a modelled map and reference data. The results show that although the quality of the DEM impacted the flood extents, the characteristics of the slope of the floodplain, perpendicular to the river flow, affected the ambiguities of the boundaries produced. In flatter regions, uncertainties in flood predictions were greater, regardless of the resolution of the DEM used. In flat plains, this uncertainty becomes infinite and restricts the capabilities of the hydraulic models in delineating the desired inundation extent thus limiting the reliability of flood risk maps for providing accurate information for flat areas.

6 ACKNOWLEDGEMENTS

We would like to thank the Swedish National Land Survey (Project: "Kvalitetsbeskrivning av geografisk information vid översvämningskartering") for making the part on disparity distances of the Eskilstuna River possible to conduct and Gävle Municipality for making the Testebo River study feasible. This combined study of both rivers is part of the Uncertainty of inundation mapping sub project under the DaGIS (Demonstration and Use of Geographical Information in the Society) project, which is financed by the European Union through Swedish Agency for Economic and Regional Growth (Tillväxtverket) (project number 151092).

REFERENCES

Brandt, S.A. 2005. Resolution issues of elevation during inundation modeling of river floods. In B-H. Jun, S-I. Lee, I-W. Seo & G-W. Choi (eds), *Water Engineering for the Future: Choices and Challenges, Proc. XXXI International Association of Hydraulic Engineering and Research Congress, Seoul, September 11-16 2005*, 3573-3581. Seoul: Korean Water Association. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-2490.

Brandt, S.A. 2009. Betydelse av höjdmodellers kvalitet vid endimensionell översvämningsmodellering. FoU-rapport Nr 35, Högskolan i Gävle. In Swedish. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-4120.

Casas, A., Benito, G., Thorndycraft, V.R. & Rico, M. 2006. The topographic data source of digital terrain models as a key element in the accuracy of hydraulic flood modelling. *Earth Surface Processes and Landforms* 31(4): 444-456. doi: 10.1002/esp.1278.

Cook, A. & Merwade, V. 2009. Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping. *Journal of Hydrology* 377(1-2): 131–142. doi:10.1016/j.jhydrol.2009.08.015.

Horritt, M.S. & Bates, P.D. 2002. Evaluation of 1D and 2D numerical models for predicting river flood inundation. *Journal of Hydrology* 268(1-4): 87-99. doi: 10.1016/S0022-1694(02)00121-X.

Hydrologic Engineering Center 2008. *HEC-RAS: River Analysis System. User's Manual, Version 4.0.* US Army Corps of Engineers, Hydrologic Engineering Center, Davis.

Klang, D. & Klang, D. 2009. *Analys av höjdmodeller för översvämningsmodellering*. In Swedish.

Lim, N.J. 2009. Topographic data and roughness parameterisation effects on 1D flood inundation models. BSc Thesis, University of Gävle. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-5039.

Lim, N.J. 2011. Performance and uncertainty estimation of 1- and 2-dimensional flood models. MSc Thesis, University of Gävle. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-9642.

Mason, D.C., Cobby, D.M., Horritt, M.S. & Bates, P.D. 2003. Floodplain friction parameterization in two-dimensional river flood-models using vegetation heights derived from airborne scanning laser altimetry. *Hydrological Processes* 17(9): 1711-1732. doi: 10.1002/hyp.1270.

Melin, S., Brandt, S.A., Tränk, L. & Rickberg, H. 2011. Översvämningsskyddsplan för Åvägenområdet i Forsby. Consulting report by Terra Firma and GeoVega. In Swedish.

Omer, C.R., Nelson, E.J. & Zundel, A.K. 2003. Impact of varied data resolution on hydraulic modeling and floodplain delineation. *Journal of the American Water Resources Association* 39(2): 467-475. doi:10.1111/j.1752-1688.2003.tb04399.x.

Raber, G.T., Jensen, J.R., Hodgson, M.E., Tullis, J.A., Davis, B.A. & Berglund, J. 2007. Impact of Lidar nominal post-spacing on DEM accuracy and flood zone delineation. *Photogrammetric Engineering & Remote Sensing* 73(7): 793-804.

Schumann, G. Matgen, P. Hoffmann, L. Hostache, R. Pappenberger, F. & Pfister, L. 2007. Deriving distributed roughness values from satellite radar data for flood inundation modelling. *Journal of Hydrology* 344(1-2): 96-111. doi: 10.1016/j.jhydrol.2007.06.024.