EFFECTS OF LIDAR DEM RESOLUTION IN FLOOD MODELLING: A MODEL SENTITIVITY STUDY FOR THE CITY OF TEGUCIGALPA, HONDURAS

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ABSTRACT:

An important aspect of hydraulic flood modelling deals with representing topography of river and floodplain. Commonly, flood model applications are reported successful in topographically simple areas were topography only changes gradually and where topography is simulated by DEM's of relatively low resolution. Such DEM's are particular useful for flood simulation in rural areas, although important topographic features and properties are not simulated explicitly. In urban areas, however, features like roads, buildings, river banks and dykes have great effect on flow dynamics and flood propagation and as such must be accounted for in the model set-up. This is possible by means of high resolution input data that relates to the systems topography as well as to the identified features. By frequent urban floodings over the past decades, an urgent need is identified to improve and increase our modelling efforts and to address more explicitly the effect model input data has on the simulation results. Society demands accurate and detailed information on magnitude and likeliness of hazardous flood events for design of flood mitigation measures. This also is the case for the city of Tegucigalpa in Honduras that severely has been affected by floodings as caused by extreme rainfall events. For the study area, a DEM with grid size of 1.5 m. is generated from LIDAR data and served as a base line case for various flood simulations. In this study, this DEM is re-sampled and DEM's of resolutions up to 15 m. are created and serve as input to the flood simulations. By the re-sampling to courser grid elements, averaging across increasingly larger domains is realized and has resulted in an increased loss of detailed topographic properties that affect flood simulations. The original DEM is also used to extract buildings by using geomorphologic filters and other GIS operations. For the simulation, buildings are represented as solid, partially solid and hollow objects by varying the surface roughness value. The sensitivity analysis to DEM resolution revealed that topographic representation is critical and that model output is significantly affected by the resolution of the DEM.

1. INTODUCTION

Societal needs to obtain reliable information on flood characteristics are increasing as the occurrence of flood events has become a common experience in many parts of the world. Besides the more frequent floods also flood damage for singular events has increased. The latter is partly caused by the tendency that more people start to live in floodplains and consequently causes that society becomes more exposed to flood damages. Clearly a better understanding on potential hazardous events is required and reliable flood simulation and "State of Art" forecasting tools must be developed further. Such tools help to map potential flood hazards but also help to develop and design flood-mitigating measures. For this, knowledge on flow characteristics of a certain flood event is a pre-requisite that must become available through flood simulation modelling. In the past, limited computational resources mainly dictated the design and complexity of the structure of such hydraulic model approaches and resulted in development and applications of one-dimensional (1D) flow models based on kinematic and diffusion wave approximations. Obviously, the reliability of simulation results was closely related to the selected model approach but also to the availability and quality of input data for model parameterisation. Difficulties to obtain accurate model input further constraint applications and several limitations have been reported that relate to the inaccurate representation of the multi-dimensional real world flow patterns and related flood characteristics. By the advent of computing resources, nowadays it is possible to apply two-dimensional (2D) model approaches that solve the shallow water equations known as the St. Venant equations. These approaches have shown to produce results that are in reasonable correspondence with available field data and generally perform better than 1D models (Marks and Bates, 2000).

Successful 2D modelling is reported for topographically simple areas where, commonly, low resolution Digital Elevation Models (DEM) are used as model input. The performance of these approaches, however, needs to be further evaluated in topographically (more) complex areas while at the same time the use of high resolution DEM's is advocated. Compared to rural areas, urban areas generally are more difficult to simulate due to the presence of small-scale system features like roads, buildings and dykes that block and affect flow patterns. This has triggered researchers and modellers to use high resolution input data for flood simulation in urban areas and floodplains with human settlements. Developments in airborne remote sensing data capturing techniques such as "LIght Detection And Ranging" (LIDAR) supported the use of high resolution data. During the time of development it was expected that airborne remote sensing such as LIDAR could provide high quality digital terrain models that could serve as input in 2D hydraulic flood modelling. Verwey [2001] e.g. stated that with the advent of airborne laser altimetry techniques for hydraulic roughness data mining from raw data and the further development of plant-flow resistance relationships, it is expected that reliability of hydraulic model approaches will improve.

In practice of hydraulic flood modelling the resolution of the DEM as obtained through LIDAR is often different from the resolution required. Commonly relatively large DEM grid elements make up the model domain in order to reduce the computation time. This to allow quick model calibrations and model sensitivity analysis but also, in operational mode, it allows flood forecasting in real time. A major disadvantage of the use of low resolution input data is the loss of important small-scale features that affect flood propagation. During the transformation or re-sampling of the original DEM data of relatively high resolution to a lower model resolution, important topographic details are lost mainly as a result of averaging. As such, there is a need to quantify on the effects such averaging has on model performance and, more important, the reliability of simulation results. Horritt et al. [2001] performed such study and used topographic information provided by LIDAR survey. With regard to the complexity of the model approach, a 1D raster based model approach "LISFLOOD-FP" was used. Werner [2001] investigated the effect of varying grid element size on flood extent estimation from a 1D model approach based on a LIDAR DEM. Horritt et al. [2002] evaluated the flood simulation results as obtained from a 1D, raster based model and a 2D model with finite element discretisation. The results indicated that simulated topographic properties had a major effect on simulation results and topography is a major factor determining flood inundation patterns as they develop over time. The mentioned studies however are performed in rural areas and applications in urban areas with very high resolution data have not gained much attention.

The aim of this paper is to show the potential of LIDAR data for the flood simulation in urban areas and evaluate the effect of the DEM averaging process, as caused by selected re-sampling procedures, on flood model simulation results.

2. MATERIALS AND METHODS

In a river system many catchment response modes can be observed ranging from extreme high flood events to extreme low flow situations. Hydraulic flow models are developed to simulate both response modes as well as the entire range of modes between these extremes. These models however only are simplified representations of the real world and are initially developed to simulate flow behaviour in a channel only. During a flood event also flood plains become inundated and simulating water flows across such plains nowadays is at the core of many flood studies. Such is also the case for the City of Tegucigalpa. In our study the SOBEK model approach is selected that applies a finite difference spatial calculation scheme. Such scheme requires a spatial distributed model domain that is compatible to most remote sensing data formats.

2.1 LIDAR Topographic Data Acquisition

Accurate representation of topography is of prime importance in hydraulic flood modelling. Flood models are able to simulate flow patterns across the model domain over a specified simulation period. The rise and lowering of the flood levels as well as flow velocities, flow directions, flood duration and inundation extent are simulated and greatly contribute to our understanding of the potential damage of a flood. For such understanding detailed and accurate DEM's are required to simulate specific properties of the real world that obstruct or conduct the flow of water but also, simulated topographic gradients contribute to the hydraulic gradients that governs the flow properties such as velocity and direction. The inaccurate topographic representation in small-scale urbanised areas may cause major set-backs and analysing this is at the core of this work.

Improvements in LIDAR data acquisition have the potential to solve the problems associated with inadequate representation of topographic data. The primary advantage of LIDAR data is the accurate digital representation, which is less subject to the horizontal errors inherent in using data sets derived from contour lines. LIDAR can produce maps of surface height over large areas with a height precision of about 15 cm. (depending on the nature of the ground cover) and a spatial resolution of about 1m. Other advantages include its rapid collection and the possibility of repeat flights over floodplains that may be subject to topographic changes. A high-resolution model will also be advantageous when small scale hydraulic processes have to be simulated that have significant effects on model results; this for example where inundation extent is controlled by small topographic features such as dykes, levees and ditches. As stated earlier, the input DEM for flood modelling often needs to be at small resolution and re-sampling LIDAR data could result in loss of important terrain information that relate to the presence of roads and dykes. An important challenge in using LIDAR data processing for flood modelling is to define the bare earth elevation that is used in the flood model to simulate (land) elevation gradients between model grid elements. Ideally data processing is supported by a field survey that also could serve to obtain specific information on hydraulic structures such as bridges and actual heights of buildings. Besides DEM extraction, LIDAR data could be used to derive base-line data on land use to derive hydraulic roughness data.

2.2 Model Approach

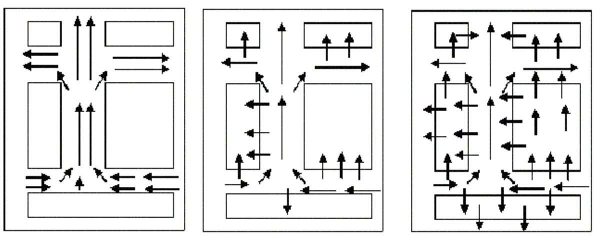
In this study, the SOBEK flood model approach was adopted. An overview of the model approach and a case study using low resolution DEM is presented by Dhondia et al. [www.sobek.nl]. In SOBEK, 1D and 2D approaches are combined and allows simulation of water flow in river reaches as well as river-bank overflow and flow at flood plains. In this study only the 2D module was activated since the DEM grid element size is smaller than the channel width.

Water movement in the SOBEK approach is described by finite difference approximation that allows the use of rectangular grids only. Any DEM as used in the SOBEK approach therefore must be raster based and topographic representations by means of a Vector DEM or Triangulated Irregular Network in flood modelling are not further discussed. In SOBEK the following three equations are solved: the continuity equation, the momentum equation for the x-direction and the momentum equation for the y-direction. In numeric term the approach applies a fractional time step method to solve the momentum balance. In the first fractional time step flow advection is calculated followed by the friction term and the pressure gradient in the second fractional time step. After substituting of the velocity term, the mass balance equation results in a linear equation for the water levels in each element. In SOBEK, the linear system of equations is calculated by use of an iterative method, called the conjugate gradient method.

The data requirements for floodplain modelling can be categorized into data input for analysis, calibration and verification. The analysis part mainly requires geometric information (channel cross section area and floodplain DEM), bed friction coefficients, boundary and initial conditions. The calibration and verification stages require independent observed flow characteristics: inundation area, flow discharge, depth and velocity. In this study this part was not undertaken since, unfortunately, field data of the event being simulated was of too poor quality. For further work in the study area such however requires attention. Simulations performed in this study therefore serve for model comparison when DEM's of different resolution are used and when land use is differently parameterised by means of hydraulic roughness coefficients.

For the City of Tegucigalpa a DEM was created from LIDAR data (1.5 m. resolution) were data acquisition was performed during the low flow season when river water depths are assumed negligible as compared to water depths during high flows. Data could thus be used without any modification for the elevation of the channel area as covered by water. Bare earth elevation heights were defined by a methodology based on a series of filters and mathematical operations. For extracting buildings, a rank (minimum) filter was used. Hydraulic parameterisation of the land surface is usually obtained through laboratory experiments under controlled conditions. For this study surface roughness values are obtained from tables as commonly presented in hydraulic hand books.

In the base line case, buildings are represented as solid objects, hollow objects or partially solid objects with large surface roughness values. For representation as partially solid objects, roughness values of 1 for buildings and 0.025 for areas without buildings are specified while for hollow object representation buildings are assumed to have the same surface roughness values as other features in the floodplain. The possible representations of buildings for flood modelling and the associated possible flow vectors are illustrated in Figure 2. In any simulation surface roughness values of 0.07 for the floodplain and 0.04 for the channel are used.



a b c

Figure 2. Flow vector when buildings are represented as a) solid objects, b) partially solid objects, or c) hollow objects

In hydraulic flood modelling, initial and mathematical boundary conditions must be defined. Initial conditions represent the hydraulic state of the system prior to the actual model simulation. It can be estimated by interpolation of the observations from available gauges, or simulated by introducing a so-called warm-up period. Defining this condition by far is trivial but it could have a great effect on the actual simulation (see Rientjes, 2004). Flood modelling also requires specification of the upstream and downstream boundary conditions. Here, a head-dependent (Cauchy) flow condition is specified that often is termed the mixed boundary condition. In such approach two hydraulic head values are required and subject to the difference a flux is calculated. One head value is defined outside the model domain by the user while the other head is calculated inside the model domain. The upstream boundary condition is provided through a flow boundary in terms of a discharge hydrograph.

3. RESULTS

3.1 DEM Re-sampling

The objective to create a DEM is to produce an accurate representation of topographic elevations and related attributes such as slope gradient and slope aspect. By re-sampling a high resolution DEM to a lower one, the size of the grid elements becomes larger but the new value depend on the re-sampling method and also on the number of grid elements used for re-sampling. In general at least two elements are used to estimate new elevation values. In this study a number of re-sampling methods, for the available LIDAR DEM of the study area with resolution of 1.5 m., are used to decide on the new value of each element. Applied re-sampling methods are the nearest neighbour, bi-linear and bi-cubic methods. In case of nearest neighbour method there is a possibility of occurrence of more than one point at an equal distance to the output grid element.

Method	Grid element size (m)	Min. error (m)	Max error (m)	Std dev. (m)	RMSE (m)	Mean (m)
Nearest Neigh.	4.5	-3.01	24.3	3.10	3.13	0.56
	7.5	-16.75	22.9	3.56	3.54	0.13
	10	-13.58	13.5	2.82	2.81	-0.18
Bilinear	4.5	-3.01	24.3	3.10	3.13	0.56
	7.5	-14.07	22.1	3.27	3.25	0.13
	10	-12.47	13.2	2.72	2.71	-0.14
Bicubic	4.5	-3.01	24.3	3.11	3.13	0.53
	7.5	-15.42	23.5	3.45	3.44	0.19
	10	-29.96	13.1	14.3	4.32	-0.45

Table 1: Results from re-sampling the 1.5 m. DEM to larger grid elements.

The bi-linear method makes the DEM smoother as compared to the nearest neighbour method as it averages neighbouring values. Bi-cubic method results in both sharpening and smoothing of the input map. Results of these re-sampling methods are presented in Table 1.

3.2 Representing Buildings

Results of flood simulations for DEM with grid size of 5 m. are given in Figure 3. Results are given for the three approaches to represent buildings (see Figure 2). The largest number of elements inundated occurs when buildings serve both as conveying objects (partially solid objects). When the size of the inundated area is normalized with respect to the maximum area this resulted in area fractions of 100%, 97.42%, and 95.65% for buildings as partially solid, hollow, and solid objects respectively.

3.3 Effects of DEM resolution on flood simulations

In the real world topography is one of the critical factors affecting the propagation of a flood wave in a channel and its surrounding floodplain. Clearly, geometrical properties of topography may obstruct to flow but also could conduct or accelerate the flow of water. In hydraulic modelling, output to a large extent is affected by model input such as the DEM and related properties such as slope gradients, slope aspects and drainage density. Understanding the relationships between flow depth, velocity and inundation area across the model domain is of great interest in modelling but are difficult to define. Understanding the 'isolated' effects of input variables such as a DEM, applied boundary conditions and applied meteorological stress conditions is even more challenging since effects may be interrelated. Also model inputs such as the hydraulic roughness, which also are simulated at the scale of the DEM elements, change with DEM resolution and as such also affect simulation results.

By using a rectangular grid DEM structure, the elevation of the area covered by a grid element becomes a lumped property and is replaced by a single value. By lumping, any spatial

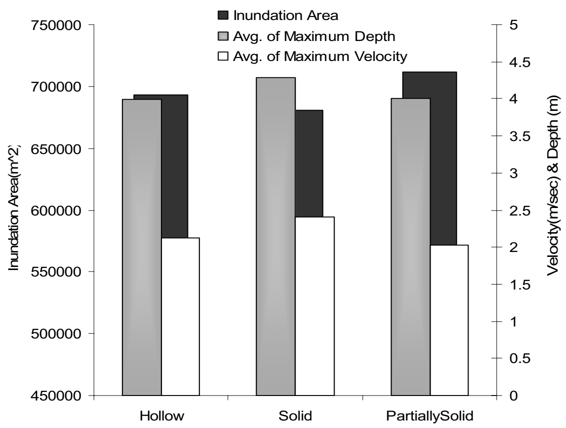


Figure 3. Bulk flow characteristics for different types of building representation

heterogeneity is ignored and results in averaging or generalization of features such as dykes and other flow obstacles but also local storage areas with sizes smaller than the selected grid element size are ignored. Clearly, averaging could result in poor flow pattern representations in particular when

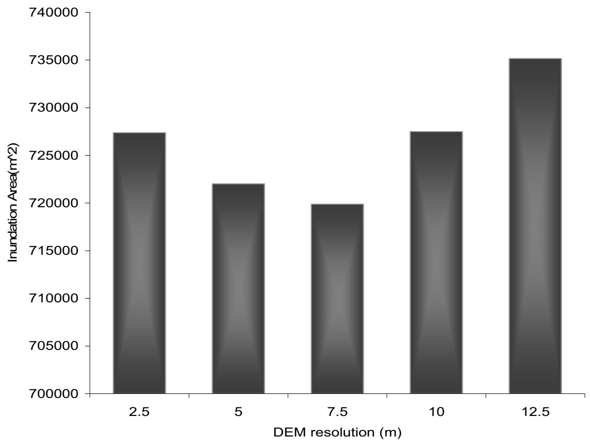


Figure 4. Maximum inundation area variation with DEM resolutions.

low resolutions are adopted. In hydraulic flood modelling it is of great interest to know to what extent the use of low resolution DEM and its associated generalization of important features affects the model outputs. Often there is a dilemma to select an appropriate resolution: a low resolution DEM results in a larger loss of information while a high resolution DEM results in excessive computational time. Calculation time for this study e.g. ranged from few hours to 13 days (1.5 GHz Pentium IV PC) for the 15 m. and 2.5 m. DEM resolution respectively. Thus, the DEM resolution should be selected in such way that computational time is 'acceptable' while averaging across larger grid elements does not generate 'unacceptable' results. To analyse simulation results in SOBEK, over the simulation period the maximum flow depths and velocities occurring within each grid element of the problem domain are stored.

Figure 4 illustrates the maximum inundation area for two applied DEM's. Since the same discharge hydrograph is introduced for the upstream boundary condition, equal volumes of water are expected to be stored in the model domain provided the same upstream and downstream boundary condition is introduced. Although cross sectional areas increase with increased element size, it is assumed that such effect can be ignored since inflow and outflow boundary elements are of equal size. This is to satisfy the law of mass conservation: for a certain time period, the inflow minus the outflow must be equal to the change in storage. Thus, a larger flood extent is usually expected to be associated with a smaller flood depth. Following this reasoning, it is surprising that this is not observed in Figure 5 and 6 and the simulation results show inconsistencies. For the 15 m. resolution DEM as compared to the 5 m. DEM, the significant increase in inundation extent and depths were found to be extremely large (see Figure 6). The combined effect of the increase of flood depths and inundation area is unexpected as well the excess in flood extent.

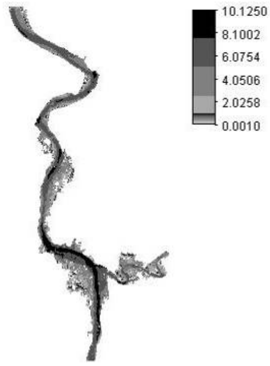


Figure 5. Maximum flood depth for 5 m. DEM resolution

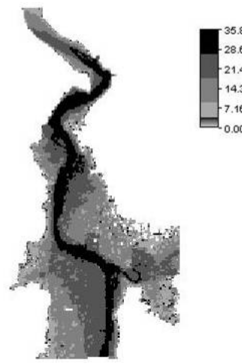


Figure 6. Maximum flood depth for 15 m. DEM resolution

4. DISCUSSION

For the low resolution DEM's (7.5 m. and 10 m.), Table 1 reveals significant differences by the re-sampling methods in terms of the magnitude of errors that are generated. For the 4.5 m. grid element size, all methods resulted in an error of similar magnitude. The bi-cubic method exposed the fact that as the grid element size increases also the error increases. However, for the other two methods the smallest error is observed for the largest grid element size (i.e. 10 m.). The bi-linear method resulted in smaller errors than the bi-cubic in two of the three cases. In all the methods, a significant error is observed indicating a considerable loss of information in transferring a high resolution DEM to a lower one. The largest error is observed by the bi-cubic method.

To explain the model phenomenon as shown in Figures 5 and 6, three reasons are anticipated. The first anticipated reason deals with the effect the selected downstream boundary condition has. In this study, a hydraulic free flow condition was introduced at the downstream end of the hydraulic model by specifying a lowered constant water level (i.e. hydraulic head). In this case and as indicated above, the computation for the last model grid element (i.e. calculation element) will be based on the computed water level at the boundary element and the specified water level at an imaginary element just outside the model domain. For such type of boundary condition, the water curvature is expected not to propagate at large distances into the model domain. Analysing this procedure, the use of DEM's

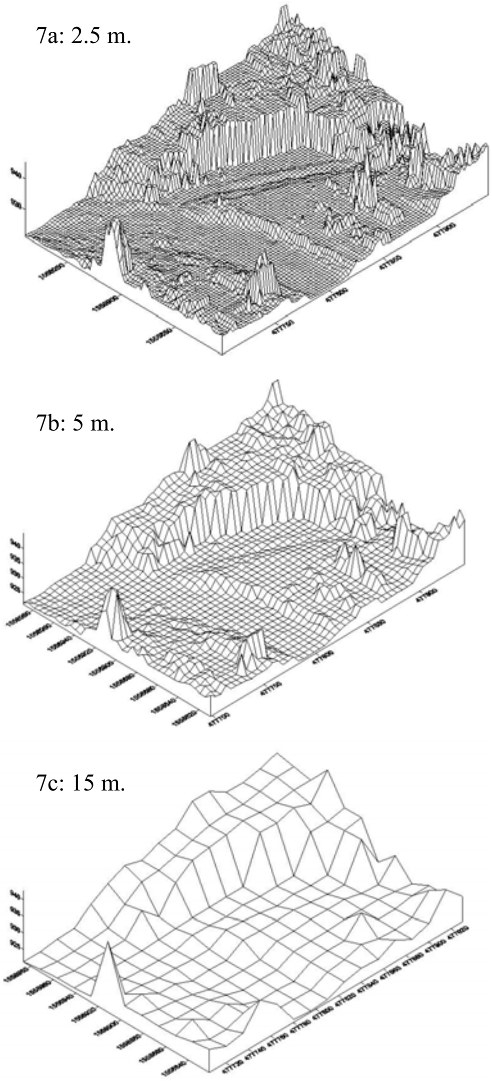


Figure 7. Effects of re-sampling in simulating flood plain topography

with increasing courser resolutions may result in different hydraulic gradients at the boundary location and thus dissimilar simulation results.

In order to test the effect of the downstream boundary condition, additional simulations are performed for the 15 m. DEM resolution. For this the channel bottom gradient at the downstream end has been made as steep as the channel gradient applied to the 5 m. DEM resolution. Analyzing the results proved that the inundation area and depths did not change significantly and thus the downstream boundary condition has no significant effect on the increase of the flooded area and the increase of flood depths.

The second reason anticipated relates to the averaging or up-scaling effect of the high resolution to the low resolution DEM. By analysing gradient distributions between the channel and floodplain grid elements, it proves that these for the 5 m. DEM generally are larger than for the 15 m. DEM. Another up-scaling effect observed is that for the 15 m. resolution DEM this resulted in an increased channel width but also dominant sub-grid element scale features were averaged out. Understanding the mathematical model approach of SOBEK, this all could largely affect the transfer of water from the channel to the floodplain grid elements. Therefore the relatively large inundation area fractions for the 15 m. DEM resolution could possibly be explained by the averaging and up-scaling. In Figure 7 effects of averaging and up-scaling are represented and an important loss of small-scale topographic information is observed. A methodology to overcome the significant loss of sub-grid scale information is to perform a GIS continuity analysis on the DEM. In such procedure it is checked whether connectivity and continuity between the parts of the problem domain is guaranteed and whether there could be flow of water from one grid element to the other. The re-sampling procedure should then be done in such a way that it maintains the features blocking or conducting water flows by manual or automatic editing of the resulting low resolution DEM. In his study this procedure is not implemented but it is only identified as a topic for further research.

The third possible explanation is that in SOBEK 2D water is only allowed to flow in 2 directions only to the perpendicular connected neighbouring elements. This introduces a difficulty to depict the flow path with a reasonable accuracy as the element size increases. This is illustrated in Figure 8 where the flow distributions vectors are shown. Considering only the shaded grid elements in Figure 8, there are outflows in the north-east and east directions of the boundary elements for the 5 m. DEM but there is an outflow only in the east direction for the 15 m.. DEM. This suggests that when using the 15 m.. DEM the element to the east of this element receives a larger volume of water than it actually receives while the element to the north of this element receives a smaller volume over the calculation time step. This problem becomes more complicated for a complex topography such as urban areas. Explaining these generic aspects of hydraulic flood and floodplain modelling requires more extensive research.

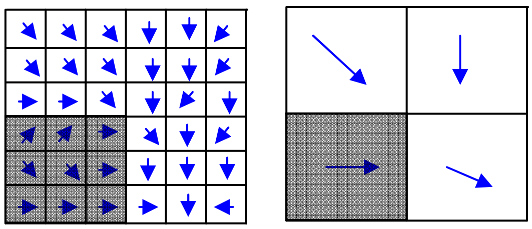


Figure 8. The effect of DEM resolution on flow vectors; left 5 m. and right 15 m. resolution

5. CONCLUSIONS

In this study different ways are explored to hydraulically represent buildings (solid, partially solid and hollow objects) in a flood model approach by varying the surface roughness values. Simulation results are compared and it is shown that bulk flow characteristics do not change significantly. It is preliminary concluded that building representation through modification of the roughness coefficient only is not sufficient to represent all hydrodynamic effects such buildings cause and generate in the real world. To quantify on this explicitly, however, requires further analyses mainly separating the floodplain and the channel and considering blocking, storage and water flow effects. A comparison of selected re-sampling methods shows that each of the methods produces an error and selecting the best method is difficult since errors do not show a clear trend.

It is concluded that the DEM resolution has significant effect on simulation results. Flood simulation characteristics that are affected are inundation extent, flow velocity, flow depth and flow patterns across the model domain. It has however not become clear by this study what generic aspect of the applied flood model approach has caused the significant differences. In this study three possible causes are identified.

Firstly, the hydraulic gradient at the downstream boundary could have an impact on the computed flood characteristics. Secondly, averaging of small-scale topographic features across larger elements causes significant losses of detailed topographic characteristics. Thirdly, at larger grid elements flow direction delineation becomes more arbitrary particular when rectangular grid DEM structure is applied which is also specific to the SOBEK flood model approach. The overall conclusion of this study is that accurate simulation of topography has significant effect on flood simulation results.

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