

UNCERTAINTY ISSUES IN HYDRODYNAMIC FLOOD MODELING

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ABSTRACT:

In flood modeling, awareness has grown that models may not be reliable and may be uncertain and that performances should be evaluated more critically. Models may be uncertain due to many reasons that commonly relate to the selected model structure, the required input but also the mathematical algorithms. In flood modeling, however, the governing flow equations are well known and nowadays efficient numerical solvers are available. With the advent of fast computing facilities it now is possible to solve the full set of equations rapidly and accurately that reduces uncertainty. However, there remain other sources of uncertainty and in this study the objective is to evaluate effects of selected boundary conditions, of applied surface roughness values and the spatial resolution of the model domain. The hydrodynamic model approaches applied in this study are the one-dimensional (1D) model, HEC-RAS, and the two-dimensional (2D) model, SOBEK.

Light Detection And Ranging (LIDAR) data is utilized to prepare a DEM and DTM for modeling the geometric and land cover inputs for the selected model approaches. In this study this data is processed by means of a GIS and inputs are prepared at various spatial resolutions to evaluate how effects of applied boundary conditions are influenced by selected grid resolution.. Model boundary conditions that are evaluated include normal depth, constant water level, artificially steeper channel, and hydraulic free flow. Results show that boundary effects propagate into the model domain at distances larger than one kilometer while the model is found less sensitive when the boundary condition is defined as hydraulically free flow. This study also shows that DEM re-sampling averages out topographic information that affects model simulation results in terms of simulated flow velocity, flood depth and flood inundation area

1. INTRODUCTION

Flood simulation models are essential to assess human, economic and financial impacts of flood inundations. Simulations may provide information on historic flooding but also are commonly used to compare and to test alternative schemes for flood damage prevention and flow regulation. Particularly distributed numeric flood models are effective for such applications since governing flow algorithms are based on conservation equations of mass, momentum and energy. In their application, equations need to be parameterized and effects of water flow into and out of the model domain has to be accounted for through imposed numeric boundary conditions.

Over the past decade, the use of advanced numeric flood models has been boosted by advances in data acquisition techniques, the availability of high power computational facilities and development of efficient numerical solvers. Research on the development of more representative flood model structures focused on a) the better simulation of mass exchange processes between floodplains, river reaches, subsurface and hill slopes that all affect flood characteristics and b) the inclusion of uncertainty methods in modeling that provide further insights to effectiveness of model parameterization, to reliability of model simulations and to process dominance (see e.g. Bates et al. [1996])

As stated in Rientjes [2004], since their early development, frequently heard criticisms in hydrologic modeling are that models are ‘unreliable, uncertain, not trustworthy and that

performances of models often are not sufficient’. Thus, it is found necessary to assess and quantify model uncertainty. Uncertainty is commonly assessed through advanced model sensitivity analyses to inputs [see Alemseged and Rientjes (2005)], by estimation of parameter uncertainty as in automated model calibration procedures or through uncertainty models [see Aronica et al (1998)].

Deviations of model calculated state outputs (V_{sim}) to observed real world state data (V_{obs}) arise from the following errors that could be positive but negative as well. But also it should be realized that errors could change on magnitude over successive calculations time steps.

- Random or systematic errors in the forcing data (ϵ_i); for example, precipitation
- Random or systematic errors in the recorded state data (ϵ_r); for example, river water levels
- Errors due to non-optimal parameter values (ϵ_{no})
- Errors due to incompleteness and use of biased model structure (ϵ_s)
- Errors due to time-space model domain discretization (ϵ_d)
- Errors due to rounding off (ϵ_{ro})

The total simulation error (ϵ_t) is equal to $V_{obs} - V_{Sim}$ and reads:

$$\epsilon_t = \epsilon_i + \epsilon_r + \epsilon_{no} + \epsilon_s + \epsilon_d + \epsilon_{ro} \quad [1]$$

For spatial discrete model domains, real world properties at grid element scale are assumed homogeneously distributed although, when compared to real world heterogeneity, system

properties vary within the selected spatial scale of grid elements. As such optimum model parameterization is far from trivial and optimum parameterization must be associated with uncertainty. Nowadays there is an understanding that uniqueness in model parameterization is questionable. Uniqueness refers to defining single best parameter sets based on available model calibration data. Over the year much literature has become available on this model calibration issue and commonly reference is made to the concept of equifinality which states multiple optimal parameter sets can be defined that all result in an equally acceptable model output (See Beven and Freer [2001]).

The objective of this research is to evaluate model sensitivity to boundary conditions, surface roughness values and topography. Two flood model approaches, the 1D HEC-RAS and 2D SOBEK, are chosen for this purpose. This study differs from Alemseged and Rientjes [2005] since in this study the main focus is on evaluating model sensitivity to the selected boundary conditions.

2. METHODOLOGY

Model approaches: The 1D model approach HECRAS and the 2D model approach SOBEK are applied for this study. Principle to 1D- approaches is that water level, velocity and discharge only change along the stream wise direction and that flow properties variation in any other direction are ignored. These models require geometrical data at chosen locations and assume that river geometry for defined river sections only changes linearly along these sections. Principle to 2D approaches is that flow characteristics change along 2 flow directions (i.e. x and y directions) following the grid layout that is defined by the DEM geo-reference. The main advantages for using 2D model approaches is that flow patterns in heterogeneous areas such as floodplains may be better represented in simulations but also flows across wide river beds is not only in one direction and require a more detailed representation of cross sections. Consequently however, difficulties with surface roughness parameterization cause calibration of 2D models to be relatively complex.

A coupled 1D2D model approach whereby the channel flow is simulated by a 1D representation and the floodplain flow is simulated by a 2D representation, is expected to benefit from advantages of each approach. The integrated 1D2D raster based SOBEK flow modeling system, developed by WL/Delft hydraulics, integrates a 1D channel flow module with the 2D overland flow module. In SOBEK 1D2D, the 2D floodplain grid layer is overlain by a 1D river layer where layers are geometrically connected through map coordinates at the centre point of a 2D floodplain grid element and the centre points of 1D river sections. The centre points of the flood plain grid layer and the centre points of the river sections make up the calculation nodes in the numeric calculation scheme and connectivity must be established to allow for overtopping of the river that cause flood plain inundations. For further information about SOBEK functionalities and solution procedures, reference is made to SOBEK online help (www.sobek.nl). In this study, only the 2D flow module is used by the availability of very high resolution LIDAR topographic data. The high LIDAR resolution cause that floodplain grid elements are much smaller than spatial dimensions of the river sections and thus in this study it is required that that river sections are simulated at a spatial resolution similar to the flood plain

resolution. This aspect of model setup is described in Alemseged and Rientjes [2005] and further explanation is ignored here. The 2D floodplain or overland flow module is based on a solution for the continuity and momentum equations.

The continuity equation reads

$$\frac{\partial \zeta}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = 0 \quad [2]$$

Where u = velocity in x-direction [L T⁻¹]
 v = velocity in y-direction [L T⁻¹]
 ζ = water level above plane of reference [L]
 h = total water depth: $\zeta + d$ [L]
 d = depth below plane of reference [L]
 x, y = distance in the horizontal direction [L]
 t = time [T]

The momentum equations in x and y directions read

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial \zeta}{\partial x} + \frac{gu|V|}{C^2 h} + au|u| = 0 \quad [3]$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial \zeta}{\partial y} + \frac{gv|V|}{C^2 h} + av|v| = 0 \quad [4]$$

Where: g = Gravitational acceleration [L T⁻²]
 C = Chézy coefficient [L^{1/2}T⁻¹]
 $V = (u^2 + v^2)^{0.5}$ = velocity [L T⁻¹]

For a full description of the terms, reference is made to text books in hydrology such as Chow [1964] and Maidment [1993].

In HEC-RAS, the total discharge is distributed to the channel and the floodplain elements as per their conveyance. The governing equations for both the floodplain and the channel grid elements are rewritten as

$$\Delta Q_T + \frac{\Delta A_c}{\Delta t} \Delta x_c + \frac{\Delta A_f}{\Delta t} \Delta x_f + \frac{\Delta S}{\Delta t} \Delta x_f - \bar{q}_l = 0 \quad [5]$$

$$\frac{\Delta(Q_c \Delta x_c + Q_f \Delta x_f)}{\Delta t \Delta x_e} + \Delta(\beta V_T Q_T) + g A \left(\frac{\Delta Z}{\Delta x_e} + S_f \right) = 0 \quad [6]$$

Where: Q = Discharge [L³T⁻¹]
 A = Cross-sectional area [L²]
 $\Phi = \frac{K_c}{(K_c + K_f)}$ [-]
 K = Conveyance [-]
 V = Velocity [L T⁻¹]
 Z = Water level [L]
 S_f = Friction slope [-]
 S = Storage term [L²]
 \bar{q}_l = Average lateral inflow [L³T⁻¹]
 β = Coefficient [-]
 ΔX_e = Equivalent flow path [L]

Subscripts C , f and T indicate terms for channel, floodplain and combined channel and floodplain respectively. In equation (6), the friction slopes for both the channel and the floodplain are assumed equal. In addition, an equal channel and floodplain water level (Z) has been used in the momentum equation.

A simple flow chart on the procedure to solve the set of governing equations by a numeric model approach is shown in figure 1. Principle in such approach is that governing equations are discretized over space and time and that a numeric solver is required to calculate model outcomes that are approximate solution of the problem. In flood modeling outcomes are flow characteristics such as flow velocity, hydraulic head distributions and flow discharges in the channel and across the floodplain. A detailed description on the applied procedures in SOBEK and HEC-RAS is ignored here since such is out of scope.

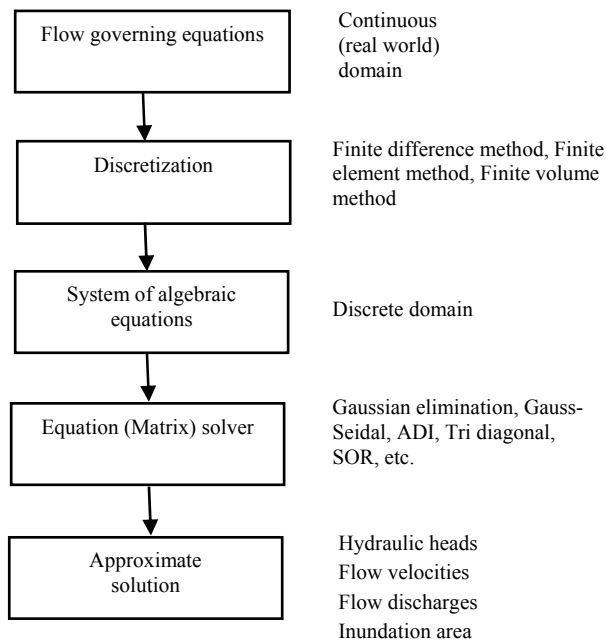


Figure 1: Flow chart on the common computational procedure in flood modeling. A remarks on each step is added in the second column

Data processing: The primary data required for flood modeling are geometric data (channel cross section area and floodplain DEM), surface roughness values, boundary and initial conditions, see figure 2. A LIDAR data acquired for the city of Tegucigalpa, Honduras, is used to extract the channel cross sections and the floodplain topography. Initial conditions are specified based on steady state simulations.

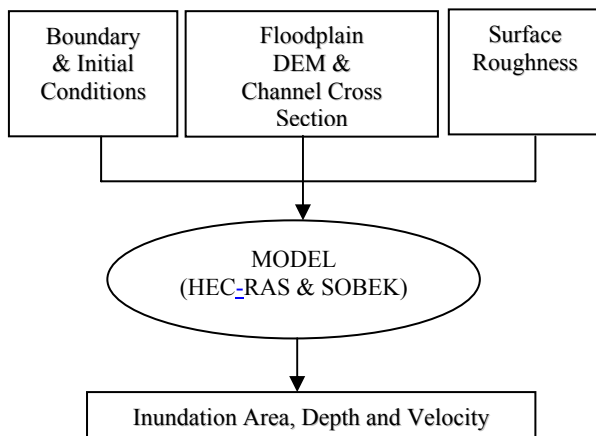


Figure 2: Diagram showing inputs and outputs of HEC-RAS and SOBEK

Geometric data: The major problem in LIDAR data post processing is how to isolate the ground surface from objects such as vegetation or buildings. The methodology commonly is to isolate bare-earth elevation from object elevations through a series of filters and mathematical operations. In this study, a slope filter and minimum filter are used to obtain footprints of buildings. Identification of an accurate building footprint map involves a trial and error procedure where the output of this procedure is compared to an ortho-photo of the study area. In figure 3 a footprint is shown. The bridges are also removed in a similar manner and the elevation values under the buildings and bridges are estimated by interpolation.



Figure 3: Building footprints overlain on an ortho-photo

The LIDAR data acquisition for the study area was performed for low flow seasons when water depths in the river were shallow and sometimes even could be assumed negligible. Based on this assumption, an ARCVIEW extension, HEC-GEORAS, is applied to extract cross sections from the LIDAR DEM. HEC-GEORAS requires a Triangulated Irregular Network (TIN) based DEM, the channel centre line and the dominant flow direction along the floodplain as inputs. It can also be used to visualize the HEC-RAS output files interface. The primary geometrical inputs required for 1D modeling are flow path centre line, main channel banks, and cross-section cut lines, and the optional geometrical inputs are levee alignment, ineffective flow areas and storage areas.

Boundary conditions: Boundary conditions are applied to define the inflows and outflows at the model boundary. Boundary fluxes are expressed in terms of mass and momentum exchanges. For flood modeling, the boundary conditions are commonly specified at inflow and outflow elements of the model domain. Numerically, three types of boundary conditions are identified: Dirichlet condition (specified head boundary), Neumann condition (specified flow boundary), and Cauchy condition (head-dependent flow boundary). The Cauchy boundary condition that is also called mixed boundary condition relates heads to flows at the outflow elements. The flow is computed based on the difference between specified heads outside the model domain as supplied by the user, and the computed heads at the boundary elements.

In this study, the 1D model sensitivity to a number of downstream boundary conditions are investigated for part of the river network located downstream of the point of

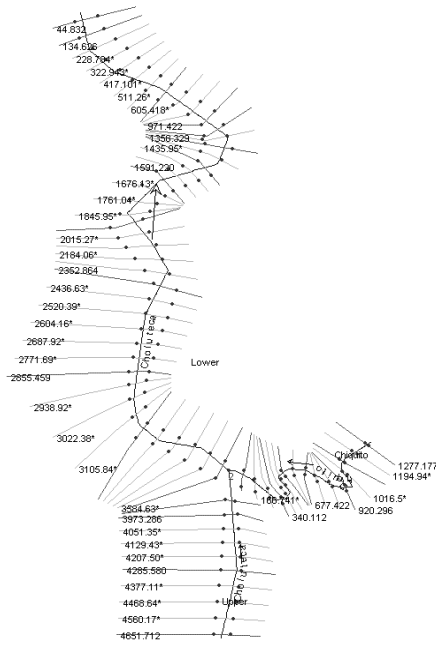


Figure 4: River cross-section cut lines as extracted from the LIDAR DEM

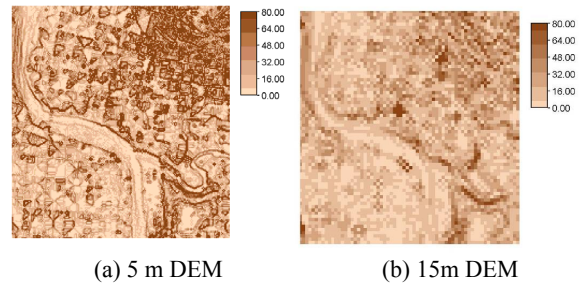
confluence. Downstream boundary conditions evaluated are normal depth, constant water levels and hydraulic free fall. In the simulations boundary outflows may change over time. The simulations are for unsteady flow where the inflow period covers 12 hours with a peak discharge of $900 \text{ m}^3/\text{sec}$ and a triangular inflow distribution while also simulations are executed for fixed upstream inflows of 50, 200, 700, 800, and $900 \text{ m}^3/\text{sec}$. The result is discussed in section 3.

For the 2D model, a head-dependent flow is specified as downstream boundary condition. This is decided based on an analysis of the HEC-RAS model sensitivity to a downstream boundary condition. Since a discharge hydrograph was not available at the upstream end for this study, a hypothetical hydrograph is constructed for peak flows obtained from regional flood frequency analysis. In order to evaluate the sensitivity to hydrographs shape, three hydrographs, i.e. normal distribution (bell shape), triangular distribution, and lognormal (skewed) distribution are considered.

3. RESULTS AND DISCUSSION

Problem domain description: Nowadays, topographical data with resolutions up to 1m spatial resolution, for instance LIDAR observations, are made available. However, the use of high resolution data for flood modeling is restricted to short river reaches because of computational expensiveness. Therefore, it is found necessary to re-sample the high resolution DEM to low resolutions.

The river bed profiles and cross-sections as extracted from different resolutions of DEM's are presented in figure 6 and 7. Figure 5 shows that topographical steepness decreases with when the DEM resolution decreases. Figure 7 shows that the 15 m DEM averages out features at smaller scale that obstruct the exchange of water between the channel and the floodplain. In Figure 8 it is shown that such affects model simulation outputs since flow velocity decreases with a decrease in DEM resolution.



(a) 5 m DEM

(b) 15m DEM

Figure 5: Slope maps

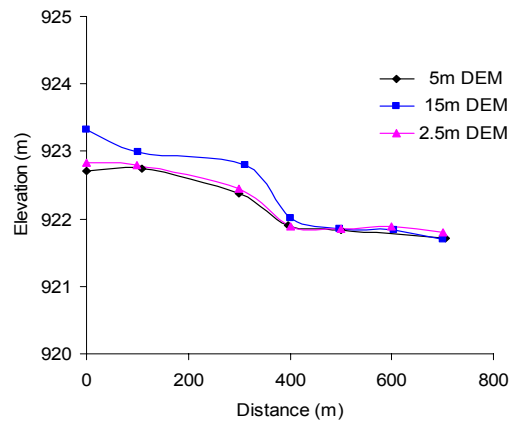


Figure 6: Channel profile at selected reach of the river

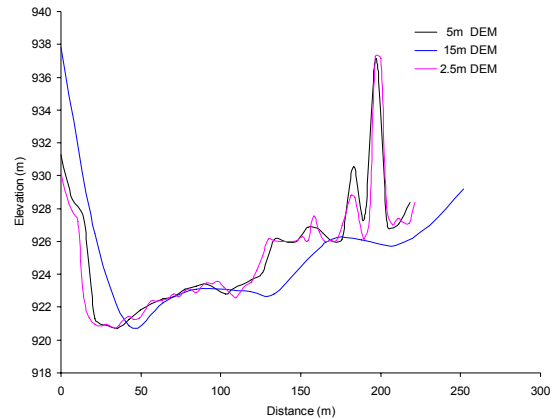


Figure 7: Channel cross sections below the junction of the river with its tributary

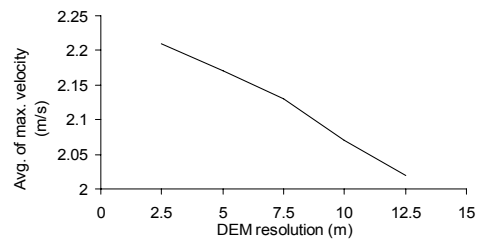


Figure 8: Variation of the average of the maximum velocity with DEM resolutions based on 2D model simulation

Boundary condition: Figure 9 shows the maximum water surface profiles for various downstream boundary conditions. From this figure it can be concluded that effects only are significant near the downstream end of the channel. Use of different cross section spacing (2m to 20m) near the downstream end results in different water surface profiles for the same type of boundary conditions. This could be caused by a steeper profile near the critical depth, which requires small cross sectional spacing for a more accurate water-surface profile representation. The downstream effect propagates up to a distance of 1500 m for a constant water level of 904m which is nearly equal to the critical depth. The distance boundary condition, which is specified at a distance of 1500m, has shown a slightly different maximum water surface profile. The 1D model is found less sensitive to the hydraulic free fall boundary condition, i.e. artificially steep channel.

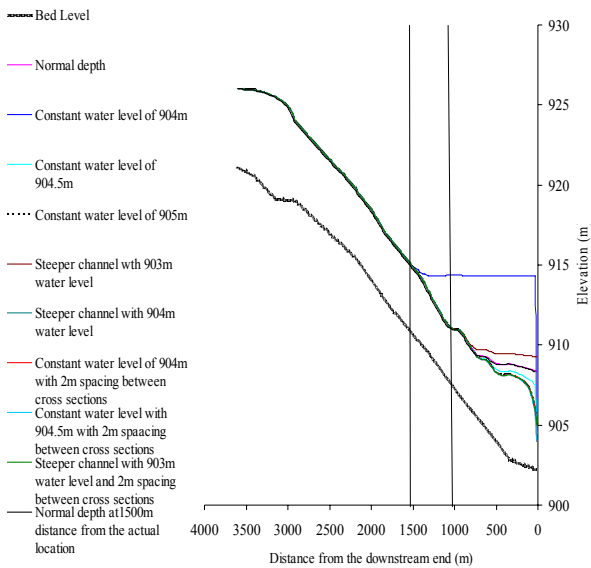


Figure 9: The 1D model sensitivity to downstream boundary conditions as evaluated based on maximum water surface profiles.

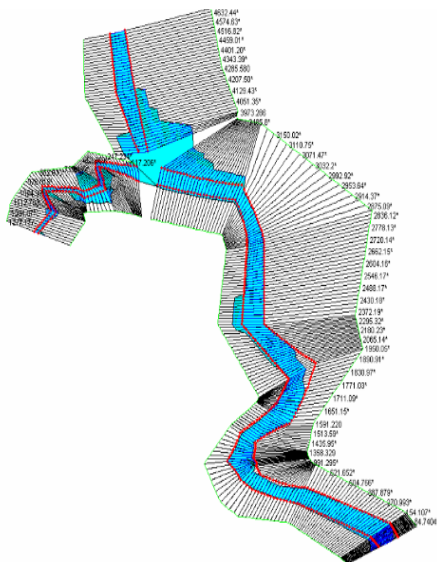


Figure 10: Inundation extent simulated by HEC-RAS (Note: the figure is rotated for visualization purpose).

As illustrated in figure 11, a normal depth boundary condition resulted in a singular relationship between the simulated stage and discharge at the downstream end. The loop effect is simulated for the distance boundary condition. This loop effect is characteristic of unsteady flow conditions and is simulated when the full governing flow equations are solved.

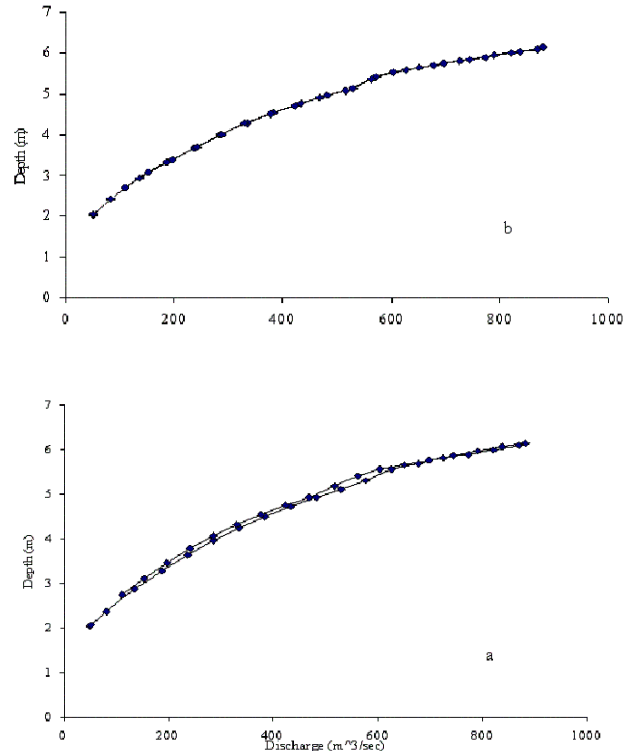


Figure 11: Rating curves at the selected downstream boundary condition location when downstream boundary condition is set a) as a normal depth, and b) as a distance boundary.

The 1D model sensitivity to downstream boundary condition is also investigated based on a steady state simulation. The locations of an equal water level for various boundary conditions are simulated at distances of 600, 750, 850, 850, and 910m from the downstream end for discharges of 50, 200, 700, 800 and 900 m³/sec, respectively.

Surface roughness: Since it is difficult to measure surface roughness, a sensitivity analysis is performed in order to evaluate the effectiveness of the specified roughness values. Although results are not presented in terms of a diagram and/or tables, it is found that the inundation area is more sensitive to the channel roughness values than that for the floodplain values. For different combinations of roughness values, equal inundation areas could be simulated and illustrates that multiple model roughness parameterizations can yield similar satisfactory simulation results. Thus as a traditional single-parameter perturbation as part of a model sensitivity analysis may not fully capture all aspects of model behavior [see also Bates et al. (1996)].

Hydrograph shape: In this study it is shown that, the shape of the hydrographs that are selected as boundary condition affects simulation results. The changes in volumes of water entered into the model domain cause differences in simulated flow characteristics. Table 1 shows the simulated flow characteristics for three hydrograph shapes. Although

significant large changes in bulk flow characteristics are not observable, analyses of individual simulation results show differences. Although it is not included in this work, analyses should be performed for equal volumes of water entered into the model but when hydrograph shapes change. Output variables of SOBEK are the maximum inundation area, the maximum inundation depth at each grid element but also the maximum and the average of the maximum simulated depths and flow velocities as shown in table 1.

Table 1: Simulated flow characteristics for different types of hydrograph shapes

Hydrograph shape	Inundation area (m ²)	Maximum depth (m)		Maximum velocity (m/s)	
		Max	Average	Max	Average
Triangular	693100	9.58	3.99	17.8	2.1
Bell Shape	698575	9.64	4.03	13.1	2.0
Skewed	695100	9.61	4.03	12.9	2.18

4. CONCLUSION

LIDAR data is used to prepare the geometrical input for the 1D model and the 2D model. The advantage of LIDAR data over the use of traditional surveying data is that cross-sections can be prepared at small intervals. This is of great importance to 1D model approaches that rely in accurate geometric representation of the river drainage systems.

In general, by re-sampling the high resolution DEM to lower resolutions, all the inputs to a 2D model such as elevation values, slope and channel dimensions are affected. It is shown that the error introduced by re-sampling affects the 2D simulation results. In this study it is for instance shown that flow velocity decreases as DEM resolution becomes coarse.

Also, for 1D model approaches it is shown that model sensitivity to downstream boundary conditions is observed at distances longer than 1 km. By analyses for different types of boundary condition, it is shown that such model is the least sensitive to an imposed hydraulic free flow. By this research, it can be concluded that a 1D model is found to be more sensitive to changes in the channel roughness values than for changes in the floodplain roughness values. For the 2D such has not yet been proven.

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