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A COMPARISON BETWEEN 1D, 2D AND SEMI 2D HYDRAULIC MODELS

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ملخص عربى

يعد إيجاد حدود الفيضان وخصائصه للمجاري المائية أمرًا بالغ الأهمية حيث أنه يلعب دورًا مهمًا للغاية في تحديد خطورتها. في هذه الدراسة تم التنبؤ بحدود الفيضان عن طريق المحاكاة الهيدروليكية والتي يمكن تصنيفها إلى محاكاة البعد الواحد والبعدين وشبه البعدين كما تمت المقارنة فيما بينهم. أثبتت الدراسة أن المحاكاة الهيدروليكية في شبه البعدين هي الأفضل حيث تعطي نتائج دقيقة ولا تستغرق وقت كبير في تهيئة النموذج وحساب النتائج وأخيرا مستقرة إلى حد كبير.

Abstract

Finding the flood plain and its hydraulic characteristics in floodways is critical as it plays a very important role in determining its risk. This research develops a general technique for performing flood plain analysis by hydraulic modeling. The hydraulic models can vary from a 1D to fully 2D hydrodynamic models depending on the complexity and the extent of river geometry. For that reason, the paper compares different 1D, 2D and semi 2D hydraulic models and their combinations in terms of the engineering applicability. The study proved that hydraulic modeling in semi two dimensions is the best where it gives accurate results and does not take much time in setup and computation times and finally it is very stable.

1. Introduction

Understanding the interaction of water flows produced by a flood on the surrounding spatial domain is critical to the flood plain risk analysis. For that reason, hydraulic models are always used in order to quantify exposure factors such as discharges, water elevations, velocities, and flooded areas. Many hydraulic models have been developed for river and coastal flooding. These models can be classified into 3 groups, each group has different capabilities and limitations that will be presented and discussed in the present study.

The 1st group is 1D models such as the river analysis system software HEC-RAS developed by the Hydrologic Engineering Center (HEC) which is a division of the Institute of Water Resources, U.S. Army Corps of Engineers. It is a software that performs 1D steady and unsteady flow calculations, sediment transport/ mobile bed computations and water temperature/ water quality modeling ((HEC) 2016). The 2nd group is called the fully hydrodynamic models such as FESWMS. It is a 2D finite element surface water computer program developed by David C. Froehlich for the United States Department of Transportation Federal Highway Administration (FHWA) and the United States Geological Survey (USGS) and it can compute the direction of flow and water surface elevation in a horizontal plane. Also has the ability to model hydraulic structures commonly used and sediment motion in rivers, estuaries, and coastal regions (SMS_User_Manual 2013). The 3rd group is called here the 2D semi-hydrodynamic models with simplification in terms of the fully 2D calculation equations, such as HEC-RAS 2D, which is version 5 of the U.S. Army Corps of Engineers HEC-RAS and it allows performing semi 2-D unsteady flow river hydraulics calculations ((HEC) 2016).

2. Problem Formulation

This research seeks to solve one of the main problems pertaining to the flood plain studies. The problem tackles the choice of the hydraulic model that should be selected to simulate the spatial hydraulic behavior in flood plain problems.

3. Hydraulic Model Selection

This section reviews the capabilities of the 3 groups of model. We consider here HEC-RAS from 1D group, FESWMS from 2D group and HEC-RAS 2D from semi 2D group. In flood inundation modeling, a distinction must be made between 1D and 2D hydraulic models.

3.1 The 1D Approach

1D models treat flow as only in the longitudinal direction. The term one dimensional derives from the model assumptions that the stage, velocity and discharge vary only in the stream wise direction and it does not explicitly consider transverse effects ((USACE) 1993). Some 1D models attempt to approximate the effects of transverse variation in roughness and velocity through the subdivision of cross sections (Gosselin, Sheppard et al. 2006). The numerical solution scheme used to solve the 1D St.Venants equations in HEC RAS is a finite difference scheme for sub or super critical flow conditions, steady and unsteady flows ((HEC) 2016). Required model parameters include topographic data in the form of a series of cross-sections, a friction parameter in the form of Manning's values across each cross-section, and flow data including flow rates, flow change locations, and boundary conditions such as a known downstream water surface elevation (Cook 2008). Water levels along the river are calculated using either basic relations between the river discharge and the corresponding water levels, or 1D flood wave progress calculations. After predicting the water levels at fixed points, they can be extrapolated to the floodplains and the inundation depths can be calculated with help of an elevation map (Weme 2005).

3.2 The Full Hydrodynamic Approach

2D models generally refer to two-dimensional, depth-averaged hydrodynamic models that compute water surface elevations and horizontal velocity components for free-surface flows in 2D flow fields (Gosselin, Sheppard et al. 2006). The numerical solution scheme used to solve the 2D St.Venants equations in in FESWMS is a finite element scheme for steady and unsteady flows, sub or super critical flow conditions (SMS_User_Manual 2013). Required model parameters for 2D model include topographic data in the form of a continuous surface represented by computational cells called mesh cells, a friction parameter for each cell in the form of a Manning's value, flow data, a turbulent parameter and boundary conditions (For example: The steady flow sub-critical simulation requires an upstream flow rate and a downstream known water surface elevation) (Cook 2008). 2D models are based on integration over the flow depth to obtain depth averaged velocity values (Weme 2005).

3.3 The Semi 2D Hydrodynamic Approach

In order to reduce the computation time and reduce numerical instability, the full St.Venants equations are often simplified by neglecting different terms in the momentum equation. These simplifications are most often applied in 2D models. While several different approximations exist, this paper will only present the main approximation used in HEC-RAS, namely the diffusive wave approximation (Betsholtz and Nordlöf 2017). The HEC-RAS 2D uses a hybrid finite difference-finite volume scheme for only unsteady flows, The module can describes sub-critical as well as super critical flow conditions ((HEC) 2016). The ground geometry is known since it is provided by the cell information. As a result, hydraulic properties (cross-sectional area, wetted perimeter, hydraulic radius and conveyance) can be computed for any water surface elevation. A water surface elevation is computed at each grid cell for each point in time (Alzahrani 2017).

In the following table a comparison between the different model groups is presented according to the present study as well as previous literature.

<table>
<tr><th colspan="2">Factor</th><th>1D</th><th>2D</th><th>Semi 2D</th></tr>
<tr><td colspan="2">Input data requirements</td><td>Cross sections Data</td><td>Digital Elevation Model (DEM)</td><td>Digital Elevation Model (DEM)</td></tr>
<tr><td colspan="2">Terrain represented by</td><td>Cross sections</td><td>Mesh cells</td><td>Mesh cells</td></tr>
<tr><td colspan="2">Setup Time</td><td>Normal</td><td>Long</td><td>Short</td></tr>
<tr><td colspan="2">Ability to represent complex river structures</td><td>Suitable</td><td>Questionable</td><td>Questionable</td></tr>
<tr><td colspan="2">Ability to represent lateral Inflow</td><td>Good</td><td>Bad</td><td>Bad</td></tr>
<tr><td colspan="2">Computation times</td><td>short</td><td>Longer than 1D and Semi 2D</td><td>Longer than 1D</td></tr>
<tr><td colspan="2">Stability problems</td><td>Better than 2D and Semi 2D</td><td>The worst</td><td>Better than 2D</td></tr>
<tr><td colspan="2">Source of instability</td><td>Cross section’s spacing</td><td>Sensitivity of using Full momentum equation</td><td>Diffusive wave approximation</td></tr>
<tr><td rowspan="7">Suitability to use in different applications</td><td>Maximum inundated areas</td><td>Suitable</td><td>Suitable</td><td>Suitable</td></tr>
<tr><td>Dynamics and velocities important (e.g. Hazard assessment)</td><td>Not suitable</td><td>Suitable and better than Semi 2D</td><td>Suitable</td></tr>
<tr><td>Few, simple structure (weirs)</td><td>Suitable</td><td>Suitable</td><td>Suitable</td></tr>
<tr><td>Many, complex (dams, gates, bridges, culverts)</td><td>Suitable</td><td>Not suitable</td><td>Not suitable</td></tr>
<tr><td>Floodplain behind levee</td><td>Not suitable</td><td>Suitable</td><td>Suitable</td></tr>
<tr><td>Simple/rural floodplain</td><td>Suitable</td><td>Suitable</td><td>Suitable</td></tr>
<tr><td>Urban floodplain</td><td>Not suitable</td><td>Suitable</td><td>Suitable and better than 2D</td></tr>
</table>

4. Case Study

This section gives an overview for a study area and the application of the different hydraulic models on it. The study area includes the "Nyamwambe" river in Uganda that will be used to simulate the floodplain using HEC-RAS 1D, FESWMS and HEC-RAS 2D models. This study used topographic datasets that are available through Pr. Dr. A. El-Mustafa who has conducted several studies on Nyamwambe River. The topographic data sets are measured in field and represented by a set of points with x (longitude), y (latitude) and z (elevation) coordinates. The following sections present a brief description of the study area, its geometry and cross section data, its land use classifications in terms of the Manning's n value, and flow data at various river stations.

4.1 Description of Study Area

Kilembe lies approximately 10 kilometers, northwest of Kasese District in the Western Region of Uganda at the foothills of the Ruwenzori Mountains close to the border with the Democratic Republic of the Congo. Nyamwamba River streams from the mountains through Kilembe village toward Lake George. Figure (1)

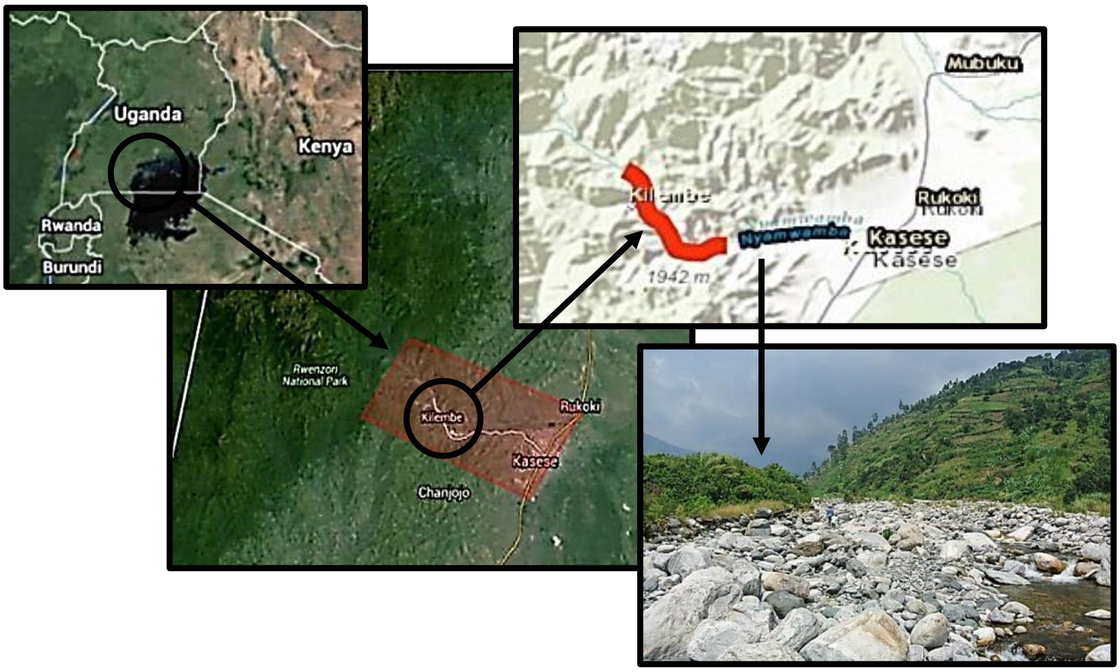

Figure (1) Study Area Location

4.2 Topography of Study Area

River Nyamwamba is characterized by meandering curves, irregular widths of banks and variations in bank levels even at the same cross section.

4.3 Flow Data of Study Area

The flow data of the river shows typically unsteady flow since the discharge through the river will usually vary with time. For simplification in the comparison of 1D, 2D and semi 2D modeling, steady peak flow is assumed as the peak discharge is constant with time. A flow of 300 m^3/sec is used for this case study.

4.4 Topography of Study Area

In this case study, Manning's value is taken 0.035 which is the value for large size rock lining. (Te Chow 1959).

4.5 Data collection and pre-processing

In Figure (2), an overview of the input data used for model set-up and boundary conditions is presented. Figure (3) shows a workflow chart for developing the 1D geometry while Figure (4) shows a workflow chart for 2D and semi 2D geometry.

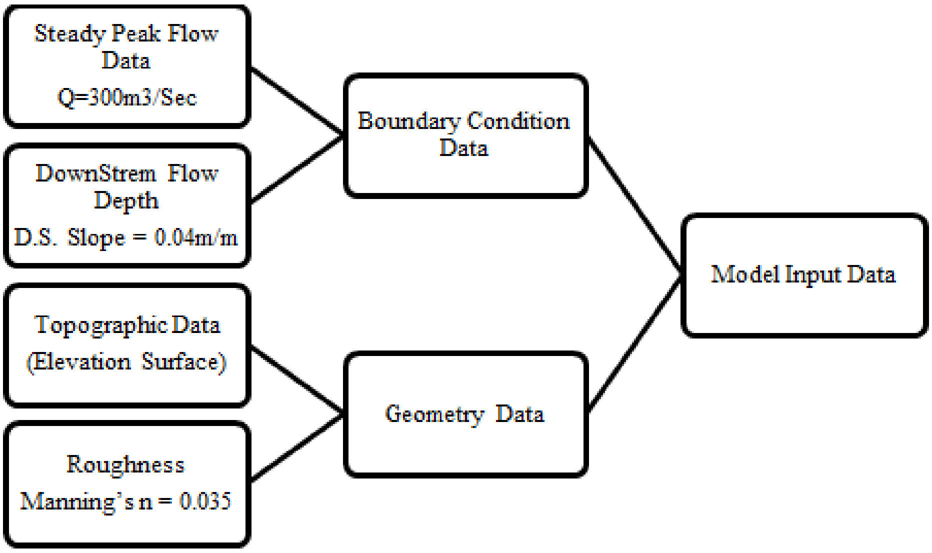

Figure (2) Flowchart Illustrating the Different Input Data in This Study

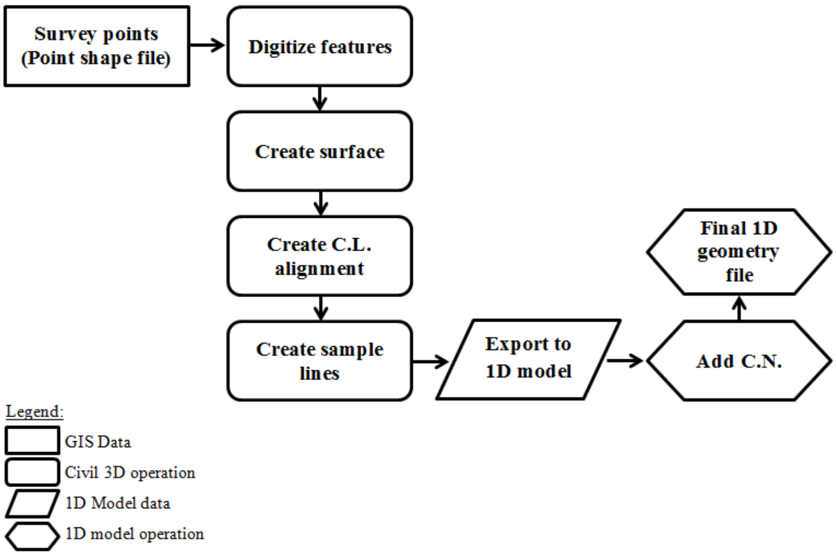

Figure (3) Work Flow for Developing the 1D Geometry File

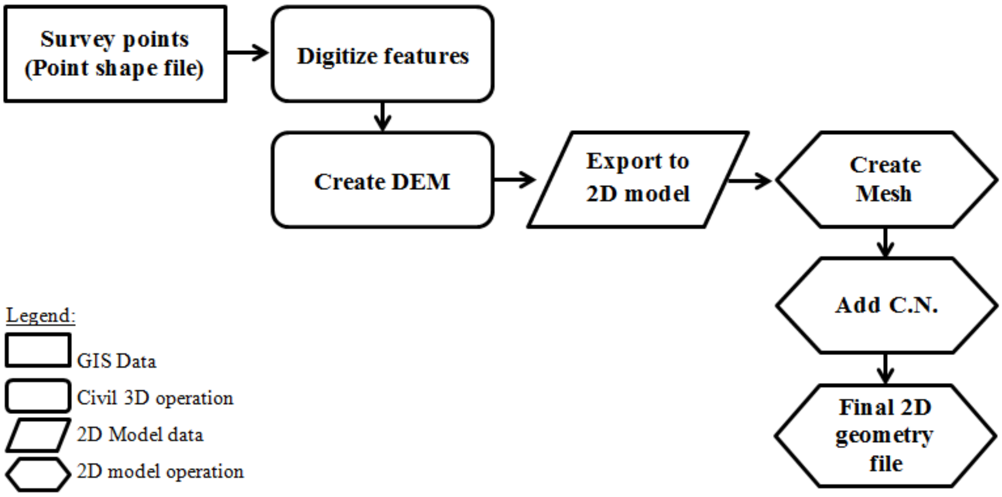

Figure (4) Work Flow for Developing the 2D and Semi 2D Geometry File

4.6 Modeling Results and Discussion

To compare the effect of geometry on 1D, 2D and semi 2D models, 3 cross sectional configurations are evaluated by determining the largest, average and minimum differences of water surface elevation (WSEL). Due to a crash in (FESWMS) when running on the full length of the river. The comparison of the case study's results will be only between HEC-RAS 1D and 2D models.

4.6.1 WSEL Comparison

The output from 1D model is in the form of water level at each cross-section's calculation point along the main channel. In 2D and Semi 2D models, the output is the computed level of water at each cell (10m×10m) of the calculation grid. Comparing the results obtained from using 1D and Semi 2D models on the full length of the river shows that there is no big difference in the water levels calculated from each model as shown in Figure (5).

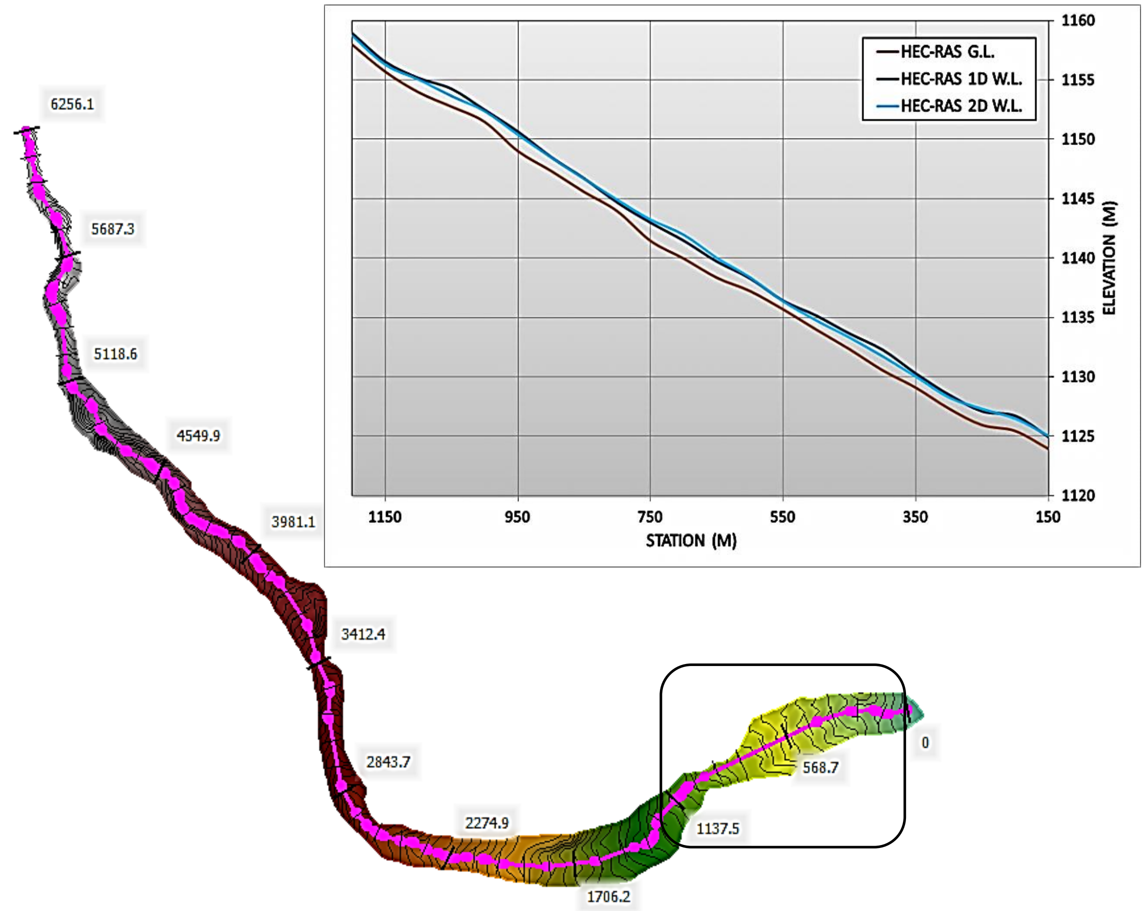

Figure (5) Maximum WSEL Profile Computed with 1D and Semi 2D Model

Figure (5) focuses on the reach from 150m station to 300m station and from station 1000m to 1150m. It is clear that in this reach there is a big variation in ground geometry (Channel bottom) which caused in the occurrence of the largest differences in maximum WSEL between 1D and Semi 2D models. The Semi 2D model takes into consideration this variation in ground geometry because it computes all hydraulic properties at each grid cell and can also compute the water surface elevation at each grid cell. While the 1D model just computes WSEL at fixed calculation points on cross-sections and between them uses the interpolation technique and does not take into consideration any changes in the characteristics of the channel. Also, the 1D model has only three cross-sections along this reach of varying ground geometry. Considering the differences in the computation techniques used by both models, it's clear that the water level in the 1D model is constant along the cross section, but the Semi 2D model results may show significant variability in the water level across the section. Table 1 shows the maximum, average and minimum DH WSEL between the 1D and Semi 2D models. The results show that the differences are not higher than 1m.

Table 1: A differences of maximum WSEL in "Nyamwambe" River

Cross Section		Max. WSEL 1D (m)	Max. WSEL Semi 2D (m)	DH WSEL (m)
5550	Maximum	1360.45	1359.85	0.60
5500	Average	1356.22	1356.04	0.18
150	Minimum	1124.95	1125.05	0.01

4.6.2 The Inundation Area Comparison

2D and Semi 2D models are conceptually an extension of the 1D approach: rather than discretizing the floodplain into several top widths of cross sections, the floodplain surface and channel are discretized into a large number of small storage. The comparison in inundation extent map in "Nyamwambe" results is shown in Figure (6). The result shows that there is similarity between the results of both models with respect to the inundation map at the floodplain area. Figure (6) shows that the solution of the 1D model significantly differs from that of the Semi 2D model. This is due to the filling process that differs between the 1D and Semi 2D models. In the 1D model the flow will start to fill the lowest ground point based on mass conservation while in the Semi 2D model, the results show how the flow moves around the floodplain area based on momentum conservation until it arrives to the lowest ground point. Table 2 and Figure (7) show the maximum, average and minimum DH WSEL between the 1D and Semi 2D models at the station of the maximum water depth. The results show that the differences are between 0.46 to 1.98m.

Table 2: Comparison of WSEL in floodplain area at the station of maximum water depth

Cross Section		Max. WSEL 1D (m)	Max. WSEL Semi 2D (m)	DH WSEL (m)
12.25	Maximum	1364.50	1366.48	1.98
32.25	Average	1364.50	1365.21	0.43
78.35	Minimum	1364.50	1364.96	0.46

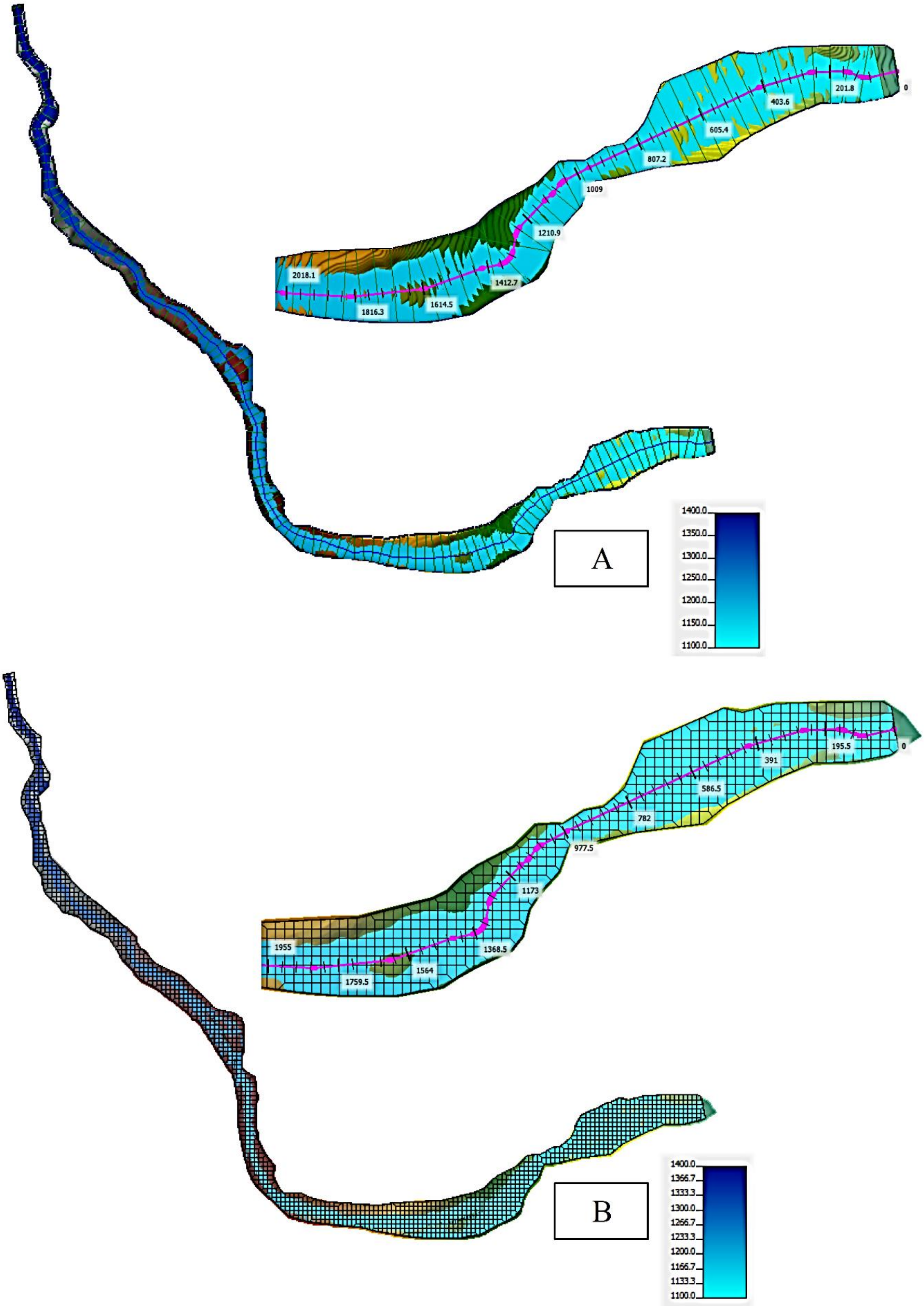

Figure (6) A Comparison of Inundation Map (A) 1D Model (B) Semi 2D Model

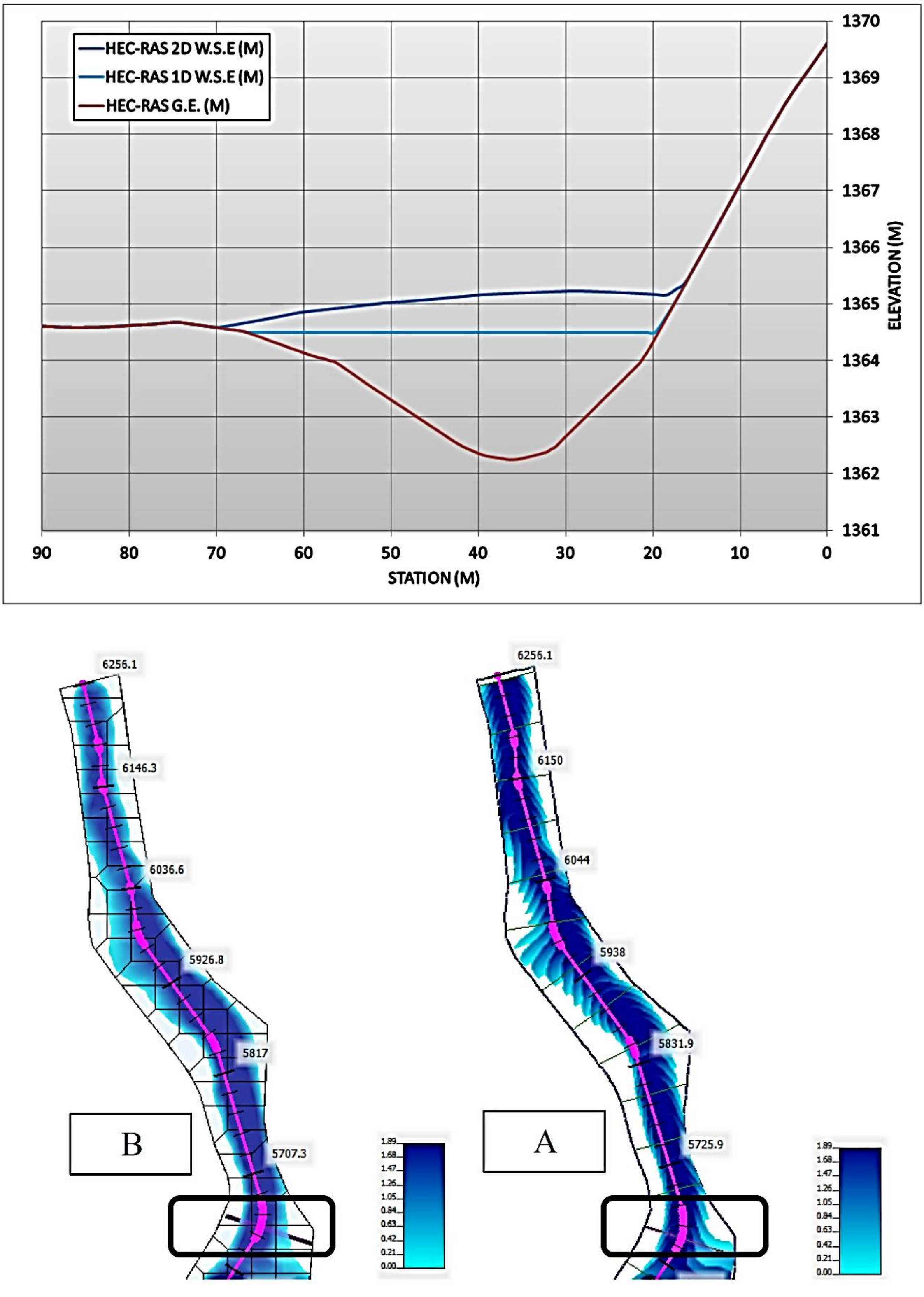

Figure (7) A Comparison of Inundation at the Maximum Water Depth Station.
(A) 1D Model. (B) Semi 2D Model

5. Conclusion

A comparison between the three hydraulic model groups (1D, 2D and semi 2D) is presented in order to help in the choice of the most suitable model to simulate the spatial hydraulic behavior in flood plain problems. A case study is also conducted on the "Nyamwambe" river in Uganda to compare the results of the three model groups represented by HEC RAS for the first group, FESWMS for the second group and HEC RAC 2D for the third group. The results are presented in terms of WSEL and the inundation area. It is concluded that, FESWMS model crashes when it is applied on the full length of the river. HEC RAS 2D is found to be better than HEC RAS 1D as it takes into consideration the variation in ground geometry and shows how the flow moves around the floodplain area and other factors that have been mentioned in the paper.

6. References

(HEC), U. A. C. o. E.-H. E. C. (2016). "HEC-RAS (River Analysis System) - User's Manual."

(USACE), U. A. C. o. E. (1993). "River Hydraulics, Engineer Manual, Waterways Experimental Station, Hydraulics Laboratory."

Alzahrani, A. S. (2017). Application of Two-Dimensional Hydraulic Modeling in Riverine Systems Using HEC-RAS, Master thesis, University of Dayton, Dayton, Ohio.

Betsholtz, A. and B. Nordlöf (2017). "Potentials and limitations of 1D, 2D and coupled 1D-2D flood modelling in HEC-RAS." Master thesis, Division of Water Resources Engineering, Department of Building and Environmental Technology, Lund University, Sweden.

Cook, A. C. (2008). "Comparison of one-dimensional HEC-RAS with two-dimensional FESWMS model in flood inundation mapping." Master thesis, Graduate School, Purdue University, West Lafayette.

Gosselin, M., D. M. Sheppard and S. McLemore (2006). Criteria for selecting hydraulic models. Transportation Research Board, NCHRP Web Document Issue Number: 106.

SMS_User_Manual. (2013). "Surface water Modeling System https://www.aquaveo.com/software/sms-learning-tutorials." V11.1.

Te Chow, V. (1959). Open-channel hydraulics, McGraw-Hill New York.

Weme, A. (2005). Quasi-2D modelling of the River Elbe: A comparison of different inundation models for flood risk assessment within a decision support system, Master thesis report, University of Twente.