EVALUATION OF DIFFERENCE MESH SIZE FOR OVERLAND ROUTING MODEL

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ABSTRACT

Two dimensional flow modelling are widely used for flood plain analysis and are considered to be a viable tool for evaluating flood propagation. The accuracy of open channel hydraulic and flood plain model is dependent on the refinement of model mesh or grid in representing ground model topography using high resolution Light Detection and Ranging (LiDAR). This paper investigates the sensitivity of unstructured mesh size of two dimensional (2D) shallow water models. The accuracy of presenting overland flood propagation was carried out using Delaunay refinement method. The study was performed by connecting to the 2D hydrodynamic modelling platform InfoWorks Integrated Catchment Modelling (ICM) using two different methodologies. The first method is based on the generation Baseline of mesh model from the digital terrain model (DTM), whereas the second method is based on the coarser of base mesh. The results of flood propagation were analysed using distinctive mesh resolutions as a part of term of surge degree and run time. The flood overland flow results as provided by the mesh techniques demonstrated all the changes when contrasted to their identical standard situations. However, further study is necessary to understand the entire performance of the two suggested methods.

Key Words: 2 Dimensional Modelling, Shallow Water Models, Unstructured Mesh, Hydrodynamic Modelling.

1 INTRODUCTION

Flooding is a chronic natural hazard with potentially devastating consequences, giving rise to a third of all losses due to natural events. Extreme weather events over the last decade have fuelled the perception that, whether due to anthropogenic global warming or otherwise, flooding is becoming more extreme, more widespread and more frequent (WMO, 2011). Two dimensional (2D) flow models have been progressively utilized as a part of flood modelling and are giving an important device in the appraisal of stream ways and along these lines the receptors of flooding.

Light Detection and Ranging (LiDAR) innovation has permitted the fast accumulation of itemized ground models for the most part at 0.5 to 1.0 m flat determination on which hydrodynamic flood model can be based. In any case, 2D hydrodynamic flood modelling is impressively more PC concentrated than the 1D models generally utilized and subsequently frequently comes about as a part of essentially expanded keep running times. This, therefore, prompts a trade-off between the runtime of the 2D model and accuracy of the model at addressing the 2D surface. The greater size of mesh components allow models to run more quickly, however, may not precisely address each one of the components of the surface.

Generally 2D hydrodynamic flood model contain either a structured grid or an unstructured mesh to represent the ground topography. Unstructured mesh have the favourable position that triangle sizes can differ within the mesh, permitting the modeller to create a better work in territories obliging point by point examination and a coarse mesh in general to accomplish sensible keep running times. The ideal 2D mesh will represent the 2D topography with adequate precision to give trust in model results while keeping up a sensible run time.

The objective of this study is to evaluate the response and performance of the shallow water model when using different mesh sizes to flood plains, subjected to the river flooding. Basically attention is given to the relationship between mesh size and model run times. Apart from that, analysis also consider the flood depth and flooded area extension in the flood plain. Shallow water models, associated to finite element and finite volume resolving schemes, allow adopting a varying degree of spatial resolution through the use of unstructured meshes, from a coarse deep water
discretization to localized refinements in the area at risk of flooding (Blanton, 2008). Moreover, the coupling of 1D-2D hydrodynamic models requires that the resolutions of each model grid/mesh in the overlapping regions are similar, to avoid the loss of information (Zundel, 2002).

2 STUDY SITE DESCRIPTION
Kelantan cover an area of 15,099 km² and is located on the North-eastern region of Peninsular Malaysia, bordered by parts of southern Thailand to the north, Perak to the west, Pahang to the south and Terengganu to the south-east. Hilly terrains are found on the southern parts of the State, separated by the Titiwangsa Mountain Range, with fertile coastal plains downstream defining the geography of the region. Figure 1 shows the Kelantan main river sub-catchment.

The river originates in the southern rugged and steep region of the state where the elevation ranges between 1,000 m to 2,000 m LSD. Meandering through the hilly areas in the upper catchment, River Nenggiri at the south-west flows in a north-easterly direction to join River Galas at Bertam. From there, River Galas flows north to capture River Pergau, which flows south easterly from Jeli, at Dabong. From Dabong, River Galas flows in northeast direction and meet River Lebir, which flows in northwest direction from Gunung Gadag, at Kuala Krai. From Kuala Krai, the river is called River Kelantan and flows towards north to the river mouth. The river length from Kuala Krai to the river mouth is approximately 100 km. The river mouth is situated about 15 km north Kota Bharu. About 760 km² of the lower river catchment has a low lying flat terrain prone to annual flooding. Kota Bharu, Kelantan has been selected for case study area.

Figure 1. Kelantan River Main Sub catchment

3 MODEL DESCRIPTION
The basic equations used in most of the one dimensional (1D) Hydrodynamic Models are based on the 1D unsteady state gradually varied flow equations (Garcia-Navarro P. and Brufau P, 2006), which are termed as the Saint Venant equations can be written as:

- the mass conservation / continuity equation:
  \[ \frac{\partial Q}{\partial t} + \frac{\partial A}{\partial x} = c \]  
  \[ (1) \]

- the momentum conservation or dynamic equation:
  \[ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{\beta Q^2}{A} \right) + gA \frac{\partial h}{\partial x} - S_0 + g \frac{AQ}{K^2} = 0 \]  
  \[ (2) \]

Where:
- \( Q(x, t) \) = discharge (m³/s)
- \( t \) = time (s)
- \( x \) = stream wise direction (m)
\( c \) = lateral inflow per unit length of flow
\( A(x, t) \) = cross-sectional area (m²)
\( g \) = gravitational acceleration (m/s²)
\( h \) = water level (m)
\( S_0 \) = bed slope (m/m)
\( K \) = conveyance (m³/s)
\( \beta \) = Boussinesq coefficient

and

i. local acceleration term
ii. convective term (responsible for non-linearity of equation)
iii. pressure term due to change in depth over reach – if \( S_0 \) is neglected, then \( dh/dx \) approximates the friction slope based on the change in water level
iv. source/gravity term causes water to flow

In some instances, Equation 1 is set equal to \( c(x, t) \, m^2/s \), which is equivalent to specifying lateral inflows from small rivers. Underground sources and ground water can influence the lateral inflow and this directly influences the calculation.

The assumptions inherent in the application of Equation 1 and Equation 2 are:

i. the flow is one-dimensional i.e. a single velocity and elevation can be used to describe the state of the water body in a cross-section;
ii. the water is incompressible with a constant density (=1000 kg/m³) uniformly distributed;
iii. the bed slope is small;
iv. the streamline curvature is small and vertical accelerations are negligible, hence the pressure is hydrostatic;
v. the effects of boundary friction and turbulence can be accounted for by representations of channel conveyance derived for steady state flow; and
vi. all functions and variables are continuous and differentiable;

Flows in flood modelling often take short cuts through flood plains where the 1D description may become quite inaccurate. This is even more the case for dam or embankment failures, where the flow may leave the flood plain completely and inundate natural terrains. For this reason the 2D shallow water equations are introduced. Following the same principles as for 1D flow, the mass conservation / continuity equation reads as below (Equation 3):

\[
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0
\]

Where, the \( y \) axis, orthogonal to the \( x \) axis, is introduced with its flow velocity \( v \) (m/s) associated to it. The convective momentum terms are subject to the same principles as discussed for the 1D approximation.

In term of the Manning’s roughness coefficient, \( \eta \), this is considered to be spatially variable according to the Earth surface cover types obtained from available aerial photos of study area. Table 2 shows the used values for \( \eta \), referred from Chow and Bunya et al.

<table>
<thead>
<tr>
<th>Land cover type</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open waters</td>
<td>0.02</td>
</tr>
<tr>
<td>Estuarine waters</td>
<td>0.025</td>
</tr>
<tr>
<td>Agriculture crop/grass</td>
<td>0.04</td>
</tr>
<tr>
<td>Natural streams, with some shoals</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Table 2. Manning’s roughness coefficient (\( \eta \)) associated to the surface of the flood plain
4 METHODOLOGY

The selection criteria of focus area are based on complex topography that will require a more refined mesh to correctly represent flow paths. Topographically complex areas are characterised by rapid changes in slope and includes features such as embankments and cuttings for roadway, railways and drainage in urban environments. The InfoWorks Integrated Catchment Modelling (ICM) hydrodynamic model was used by utilizing different mesh sizes. ICM uses an unstructured triangular mesh using Delaunay refinement method and possesses a range of features for mesh editing, import/export from GIS tools and a powerful visualisation engine, which make it ideal for running these meshes in a case study catchment.

4.1 Model Calibration
Calibration of the 2D model will be carried out using observed water levels at Jeti Kastam, Kota Bharu during the December 2014 flood event. This flood was the largest event recorded in 50 years (DID, 2015) and very useful to accurately calibrate storage volumes in Kota Bharu floodplains. The set of fit statistics which is Pearson Correlation Coefficient and Nash-Sutcliffe Efficiency will be used for hydrodynamic model calibration.

4.2 Baseline Model
An initial mesh, called baseline has been created using a standard meshing algorithm. Standard mesh size with resolution on 1m² was generated as baseline case to replicate 2014 flood event. This baseline model will be used as reference to other scenario simulated for this study. The 1m² size of mesh uniform resolution is extended in flood plain with area of 757.39 ha Kota Bharu Town. The Baseline Mesh Model (Figure 2) has 2,344,842 numbers of vertices, 4,681,410 numbers of triangles, and 3,994,185 numbers of 2D elements.

![Figure 2. Baseline Mesh Model (a) in 2D view and (b) in 3D view. Both views were overlaid with DTM generated from LiDAR.](image)

<table>
<thead>
<tr>
<th>Model</th>
<th>maximum mesh zone triangle size</th>
<th>numbers of vertices</th>
<th>numbers of triangles</th>
<th>numbers of 2D elements</th>
<th>total time for mesh generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1m²</td>
<td>2,344,842</td>
<td>4,681,410</td>
<td>3,994,185</td>
<td>0:04:24</td>
</tr>
<tr>
<td>Model 1</td>
<td>5m²</td>
<td>941,493</td>
<td>1,877,435</td>
<td>1,856,542</td>
<td>0:01:38</td>
</tr>
<tr>
<td>Model 2</td>
<td>10m²</td>
<td>471,621</td>
<td>939,200</td>
<td>797,499</td>
<td>0:00:48</td>
</tr>
<tr>
<td>Model 3</td>
<td>20m²</td>
<td>236,384</td>
<td>469,641</td>
<td>398,812</td>
<td>0:00:23</td>
</tr>
<tr>
<td>Model 4</td>
<td>50m²</td>
<td>94,866</td>
<td>187,473</td>
<td>185,501</td>
<td>0:00:08</td>
</tr>
<tr>
<td>Model 5</td>
<td>100m²</td>
<td>47,802</td>
<td>93,820</td>
<td>79,952</td>
<td>0:00:04</td>
</tr>
<tr>
<td>Model 6</td>
<td>200m²</td>
<td>24,201</td>
<td>46,909</td>
<td>39,978</td>
<td>0:00:02</td>
</tr>
<tr>
<td>Model 7</td>
<td>500m²</td>
<td>9,982</td>
<td>18,772</td>
<td>18,562</td>
<td>0:00:01</td>
</tr>
<tr>
<td>Model 8</td>
<td>1000m²</td>
<td>5,200</td>
<td>9,340</td>
<td>7,998</td>
<td>0:00:01</td>
</tr>
</tbody>
</table>
4.4 Fit Statistic for Model Calibration

The calibration process of the 2D hydrodynamic model is a trial and error iterative process, during which a set of modelling parameters are adjusted until the simulated water level are in a good agreement with the observed data at the selected gauging station. The selected station is a water level station named Jeti Kastam which is located at Kota Bharu. The model was calibrated for duration from December 17, 2017 to January 1, 2015 flood event and analyses using fit statistics which is Pearson Correlation Coefficient, Correlation Coefficient and Nash-Sutcliffe Efficiency (NSE), defined as:

$$ r = \frac{N \sum xy - (\sum x)(\sum y)}{\sqrt{(N \sum x^2 - (\sum x)^2)(N \sum y^2 - (\sum y)^2)}} $$

$$ r = \frac{1}{n-1} \sum \left( \frac{x-x^\prime}{S_x} \right) \left( \frac{y-y^\prime}{S_y} \right) $$

$$ NSE = 1 - \frac{\sum_{i=1}^{n} (Q_{sim_i} - Q_{obs_i})^2}{\sum_{i=1}^{n} (Q_{obs_i} - \bar{Q}_{obs})^2} $$

4.5 Model Performance Indices for Model Convergence Scenario

In order to quantify the discrepancy between the baseline model and other mesh sizes, and assessing the model sensitivity to mesh configurations, a set of statistical indices frequently used in the optimization of hydrodynamics (French JR, 2010) model is used. The Nash-Sutcliffe Efficiency (NSE), Mean Absolute Error (MAE) and Root Mean Square Error (RMSE), defined as:

$$ MAE = \frac{\sum_{i=1}^{n} |Q_{sim_i} - Q_{obs_i}|}{n} $$

$$ RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Q_{sim_i} - Q_{obs_i})^2}{n}} $$

$$ NSE = 1 - \frac{\sum_{i=1}^{n} (Q_{sim_i} - Q_{obs_i})^2}{\sum_{i=1}^{n} (Q_{obs_i} - \bar{Q}_{obs})^2} $$

Both MAE and RMSE provide statistical error estimation in the variable unit, while NSE is a normalized performance index, with efficiency of one perfect reproduction of an event.

5 MODEL EVALUATION

5.1 Model Calibration

Calibration of the 2D hydrodynamic model was carried out using observed water levels at Jeti Kastam, Kota Bharu during the December 2014 flood event. This flood was the largest event recorded in 50 years and so was useful to accurately calibrate storage volumes in Kota Bharu floodplains. Based on the analysis, calibration curves at Jeti Kastam, Kota Bharu is shown in Figure 3. The calibrations curves show good agreement between observed and simulated water levels, both in terms of peak water levels and time to the peak. Statistics, as well as correlation factors, are summarised in Table 4.
5.2 Results

Here a series of meshes, generated for the Kota Bharu according to different meshing sizes are tested in an eight scenarios. The chosen meshing sizes represent the possible discretization approaches on which modeller relies when dealing with shallow water finite element and volume models. In order to understand which meshing sizes guarantee an acceptable performance, the accuracy in reproducing the free water surface elevation, the flood depth, the depth average speed, flood extent, and total 2D simulation time are assessed. The evaluation of the proposed discretization on a quantitative basis, the performance indices MAE, RMSE and NSE are evaluated at Site A, B, and C (Table 5 and Figure 4).

Analysis on water surface elevation, flood depth and depth averaged speed does not show significant relationship with mesh sizes. Even though Site A, B and C are having the same catchment characteristic, the performance indices for different mesh size are varies, and do not show specific trend with respect to increasing mesh sizes. Figure 4 shows the performance plots 8 models for meshes at Site A, B and C.

It can be assumed that satisfactory resolution for Site A should be come with the flat area of the slope at the selected area compared to the Site B and C, and therefore responsible of better model behaviour with respect to other meshes size. This result is giving another perspective with the logical perception of the 2D hydrodynamic modeller, who introduces more refinement where more accuracy is desired. This result also shows there is a need to have a very careful consideration when selecting and introducing different mesh size at any particular area.

Table 5. Performance indices for meshes at Site A, B and C.

<table>
<thead>
<tr>
<th>Site</th>
<th>Water Surface Elevation (m AD)</th>
<th>Flood Depth (m)</th>
<th>Depth Averaged speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAE</td>
<td>RMSE</td>
<td>NSE</td>
</tr>
<tr>
<td>Site A Baseline</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Model 1</td>
<td>0.00</td>
<td>0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>Model 2</td>
<td>0.00</td>
<td>0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>Model 3</td>
<td>0.02</td>
<td>0.02</td>
<td>1.00</td>
</tr>
<tr>
<td>Model 4</td>
<td>0.02</td>
<td>0.03</td>
<td>1.00</td>
</tr>
<tr>
<td>Model 5</td>
<td>0.04</td>
<td>0.23</td>
<td>0.98</td>
</tr>
<tr>
<td>Model 6</td>
<td>0.06</td>
<td>0.33</td>
<td>0.95</td>
</tr>
<tr>
<td>Model 7</td>
<td>0.09</td>
<td>0.41</td>
<td>0.92</td>
</tr>
<tr>
<td>Model 8</td>
<td>0.11</td>
<td>0.41</td>
<td>0.92</td>
</tr>
<tr>
<td>Site B Baseline</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Model 1</td>
<td>0.00</td>
<td>0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>Model 2</td>
<td>0.01</td>
<td>0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>Model 3</td>
<td>0.04</td>
<td>0.23</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Table 6. Results comparison using different meshes at the study area

<table>
<thead>
<tr>
<th>Model</th>
<th>Effective Area (ha)</th>
<th>Maximum flooded area (ha)</th>
<th>Total 2D simulation time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>603.60 (100%)</td>
<td>531.09 (87.99%)</td>
<td>848,902.06</td>
</tr>
<tr>
<td>Model 1</td>
<td>529.19 (87.67%)</td>
<td>232,387.07</td>
<td></td>
</tr>
<tr>
<td>Model 2</td>
<td>527.82 (87.44%)</td>
<td>75,190.48</td>
<td></td>
</tr>
<tr>
<td>Model 3</td>
<td>603.60 (100%)</td>
<td>20,339.89</td>
<td></td>
</tr>
<tr>
<td>Model 4</td>
<td>526.91 (87.29%)</td>
<td>7,346.30</td>
<td></td>
</tr>
<tr>
<td>Model 5</td>
<td>524.64 (86.92%)</td>
<td>2,229.65</td>
<td></td>
</tr>
<tr>
<td>Model 6</td>
<td>519.71 (86.10%)</td>
<td>939.99</td>
<td></td>
</tr>
<tr>
<td>Model 7</td>
<td>516.50 (85.57%)</td>
<td>435.67</td>
<td></td>
</tr>
<tr>
<td>Model 8</td>
<td>518.76 (85.94%)</td>
<td>229.59</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Performance plots 8 models for meshes at Site A, B and C. (a), (b), and (c) is the bar chart while (d), (e), and (f) is the scatter plot matrix for performance indices.
Analysis of model performance using different mesh size was also conducted with respect to flood coverage and 2D simulation time. Table 6 shows trend of decreasing flood coverage with increasing mesh size. This happens because the volume-depth and flow-area-depth relationship in each of the mesh triangle derived from a DEM. Heights at the vertices of the generated mesh elements calculated by interpolation from a DEM, resulting in different impact of flow path at the specified area with respective mesh. Figure 5 to Figure 13 shows the extent of flood coverage with different mesh sizes. Some particular site and model also shows significant difference in flood depth and flood coverage, depending on mesh sizes (Figure 7 and Figure 8 for Site A).

Result also shows finer mesh size will result in longer simulation period. The simulation time is not favourable for very fine mesh. This is because the meshing algorithm generates very small triangles which have the effect of decreasing the time step of the 2D hydrodynamic model, leading to an increased run time. It is appear that, with the small different between baseline and model 8 with only 2.05%, clearly show that for similar level of accuracy and giving magnitude faster in run time.

6 CONCLUSIONS

Utilization of flexible mesh technique are very powerful and flexible for modelling 2D overland flows in a complex urban environment. However, complex geometries can be challenging for many modellers to deal with. This paper shows result of several meshing sizes for two dimensional shallow water models, tested for the discretization of the meshing sizes. Further research is required into this topic to understand the sensitivity of the meshing sizes an as well as the DEM and infrastructure in the flood plain.

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