FLOODPLAIN INUNDATION SIMULATION USING 2D HYDRODYNAMIC MODELLING APPROACH

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Floodplain Inundation Simulation Using 2D Hydrodynamic Modelling Approach

by

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Abstract

In this study a two dimensional hydrodynamic flood modeling approach is developed for a 30-km reach of Sungai Sarawak, Sarawak, Malaysia. Over the years, the city along this reach experienced frequent flooding and has caused a major damage to the highly populated urbanized area local infrastructures. As such a need was identified to map the area prone to flooding using an advanced hydrodynamic distributed model. The model is based on the SOBEK 2D approach that is a two-dimensional fully hydrodynamic numerical approach that allows for simulation of complex flow patterns over floodplains and urban areas. A LiDAR derived digital elevation model (DEM) was used to represent topography over the floodplain and to provide accurate hydrological bare earth elevations as required by the numeric solver. Model results for the February 2003 flood events were evaluated for DEM grid resolution of 20m with specified boundary and given initial condition. For model calibration purposes, the observed and mapped flood extent is visually as well as quantitatively compared to the simulated flood extent. The results showed satisfactorily simulation results in terms of flood timing and maximum flood depth as recorded. A simple model sensitivity analysis revealed that simulation results are affected by factors such as selected grid resolution and parameterization of flood plain and river geometry. A detailed analysis on such factors however has been ignored and is a topic of future research. This research serves as an example how advanced modelling combined with LiDAR data can be used to support the development of efficient strategies for flood emergency and evacuation but also for designing flood mitigation measures.

Keywords: LiDAR, digital elevation model, Flood modelling
Acknowledgements

What is important is to keep learning, to enjoy challenge and to tolerate ambiguity. In the end there are no certain answers.  

Martina Horner

Praise to GOD, for giving me strength, sharp minds and for HIS continuous blessings throughout my studies and stay here in the Netherlands.

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To my husband Ben, for your love, support and encouragement than anyone could ask for; this thank you isn’t enough.

Enschede, February 2007
Edna M.R.
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## Abbreviations

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<th>Description</th>
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<tr>
<td>ASCII</td>
<td>Raster file format</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DID</td>
<td>Department of Irrigation and Drainage</td>
</tr>
<tr>
<td>Sg</td>
<td>Sungai (river)</td>
</tr>
<tr>
<td>SSRS</td>
<td>Sungai Sarawak Regulation Scheme</td>
</tr>
</tbody>
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1. INTRODUCTION

1.1. Floods

Floods are among many natural disasters that hit mankind in its most delicate and harsh alike, irrespective of geographical locations and times. The amount of losses and hardships that comes along with it is sometimes unbearable for the individual, community as well as the government to cope. Floods may come in many forms depending on what factors trigger the problems. To the scientific communities, the floods perspectives are broader than one can imagine – changes in world climatic affecting the hydrological water balance and geomorphologic right to complexities in balancing the societal and environmental needs. In literatures, a large number of studies have been conducted and researchers from various disciplines try to understand the real cause and effects floods have. Nevertheless flood are witnessed frequently and the number of studies and research has increased to understand this Mother Nature’s act of flood.

Mankind does not have much choice rather than to accept the floods. Therefore, to live with the floods both have to have certain level of understanding; floods can be alleviated but not totally eliminated. The floods disaster either occurs naturally or by mankind induced such as modifying the natural flow behaviour of the flood with construction of flood alleviation structures such as dams, dykes, embankments or gates. Floods is a temporary conditions of partial or complete inundation of normally dry land area which may last from hours, days and months. Floods are affected by many properties such as catchment areas, precipitation duration and intensity, topography, land cover and geomorphologic conditions.

Coping with floods refers to all measures which mankind can undertake to alleviate impacts of floods. Numerous numbers of measures and technology are introduced to alleviate or to cope with floods. Measures can be grouped as ‘do-nothing’, structural, non-structural and a mixture of both. Do-nothing refers to not making any adjustment or modification to the landscape as opposed to the structural measures whereby extensive land surface modification is imposed to modify the flood flow behaviour. The non-structural measures seem to be on the soft side of coping and alleviating the floods because it takes the environment it belongs to into consideration.

Flood modelling is an interdisciplinary study that involves hydrologic, geomorphologic, and environmental, just to name few. Various hydrologic/hydraulic models to simulate flooding have been developed in the past and still undergo continuous improvements. Firstly, one needs to understand the behaviour of the floods in any attempts to evaluate flood characteristics and understand hydrological processes. For this purpose, knowledge on the flood such as its occurrence temporally and spatially is at utmost importance to mitigate the damages caused. An ability to map the actual extent of
inundation, timing and propagation as well as its intensity along with predicting or forecasting flooding extent are still subjects that requires continuous efforts in research. However, most of these models cover only a small area and relatively short river reach. Over the years, these models are also integrated or linked with state of the art technologies such as remote sensing and geographic information system (GIS) for time series analysis and visualisation.

In many countries as well as in Malaysia, in principal the responsibility to provide a master plan for country wide flood management strategies is the responsibility of government agencies such as the Department of Irrigation and Drainage (DID). DID introduced soft-engineering approaches of ‘retain the rainwater at source’ in contrast to draining all the water through a manual called Stormwater Management Manual for Malaysia (MSMA). MSMA is a combination of semi natural non structural measures which is built into the surrounding landscape to make it environmentally safe and friendly. The overall concept of ‘retain the rainwater at source’ is by controlling stormwater via encouraging natural retention such as more vegetation and infiltration. In a way, it not only reduces the quantity of runoff but maintain the water quality. Obviously, this approach is still at it very infant stages in Malaysia and need more comprehensive and integrated approach incorporating all stakeholders to make it a successful one.

1.2. Outline of this thesis
Chapter 1, the introductory discusses the background with factors pertaining to the flooding in general.

Chapter 2 describes the study area and the situation within the catchment, problems in the study area, the research objectives and related questions.

Chapter 3 is devoted to review of literatures related to the concept in hydrodynamic modelling applied in this study as well as describing the principle of LiDAR.

Chapter 4 is dedicated to data requirements, its processing and model simulation

The results from simulations are analysed and discussed in Chapter 5.

Finally, in Chapter 6 the conclusions and recommendations for future research are presented.
2. STUDY AREA AND STUDY MOTIVATION

2.1. Sungai Sarawak Catchment, Sarawak, Malaysia

Sarawak is Malaysia’s largest state located on the island of Borneo. It is located between longitude 109° 36’ E and 115° 40’ E and latitude 0° 50’ N and 5° N. The catchment of Sg Sarawak covers an area of approximately 1500 square kilometres. Sg Sarawak has two main tributaries; Sg Sarawak Kiri and Sg Sarawak Kanan which drained the upper catchment with the main river flowing through the city centre along the lower reaches as shown in Figure 2.1 below.

Topographically, Sg Sarawak catchment varies from a highly mountainous in the south bordering the West Kalimantan, Indonesia at 1233 metres above mean sea level (LSD) to relatively flat and typically of a low-lying floodplain to the last 10 km towards the coastal. The floodplain is wide and frequently suffers from seasonal flooding within the towns and its surroundings.

Typically, Sarawak has a tropical climate with hot and humid all year round with average temperature ranging from 23°C to 32°C. Mean annual rainfall for Kuching is around 4000 mm that is very much influenced by the monsoon season from November until March. During this season, the monsoon winds frequently carry heavy rains within the catchment.

Geologically, the catchment is overlain with Quaternary deposits consisting of coastal and riverine alluvium deposits (clay, silt, sand, gravel and peat). The soils in the downstream reaches are covered with Rajang and Bijat series soils which consist mainly of clay and large tract of Anderson peats with over 3 metres deep found just upstream of Kuching. The mountainous area upstream of the confluence consists mainly of limestone, shale, sandstones and conglomerate. The soils are predominantly of fine clay and sand.

2.2. Study Area

The study area is a 30 km stretch of Sg Sarawak from the confluence of Sg Sarawak Kanan and Sg Sarawak Kiri down to Pending as shown in Figure 2-1. This study area is a mix of urban and suburban areas and covers the highest populated area in the Kuching City. Kuching is the capital city and the administrative centre for Sarawak making it the highest populated city in the state. To mitigate runoff, drainage and stormwater infrastructures have been constructed within the study area during the last ten years. Upstream of the study area, the land use is developed for small holding agricultures, plantations and forest.

\[^1\] Land and Survey Datum
2.3. Research Problem

Almost every year, low lying areas within Kuching experience severe inundation during “Landas” season – local definition for the period of heavy downpour where the monthly rainfall is higher than the average month. This occurs normally during the monsoon season from November till March. From long series of recorded rainfall over the catchment, an increase in the amount of rainfall is observed upstream and within the catchment of Sg Sarawak especially during the monsoon seasons. Almost every year, certain areas within the catchment experience severe flooding and new areas are affected with no less in area of coverage. The increase in impervious areas is considered as one of the factor accelerating the runoff.
In 1997, Sg Sarawak has undergone large geomorphologic changes at the downstream area with the completion of the Sungai Sarawak Regulation Scheme (SSRS) that consists of the barrage, shiplock and bridge as shown in Figure 2-2. After the completion of the barrage, it is reported that there a decrease in rise of flood prone areas near or towards the barrage. However not much changes with the flood extent at the upstream of the study area. The possible causes that could have accelerated this situation is the reduced areas for flood storages on the floodplain due to rapid development along the Sg Sarawak.

Figure 2-2 : Location of the Sungai Sarawak Regulation Schemes

In this study, the February 2003 flood event was selected for simulation since for the event a flood ground survey of maximum flood levels are available to allow for comparison of observation and simulation results.

2.4. Research Objectives

The objective of this study is to simulate the flood inundation extent and timing for the February 2003 flood event using 2-dimensional modelling approach.

2.5. Research Questions

1. What effect does the raster DEM resolution has on floodplain simulation results?
2. What mathematical boundary condition need to be applied to the model?
3. How to parameterize the river geometry for the modelling?
4. How to calibrate the model simulations for flood inundation extent and flood wave timing?
3. LITERATURES REVIEW

3.1. Floodplain Modelling

For an appropriate model selection, it is important to understand the purpose of the model and the applications it is selected for. Models come in different types and were developed for different purposes. Approaches used for specific hydrologic problems are categorized into five basic components; system characteristics, input, the governing equations, initial and boundary conditions and output (Singh, 1995) as shown in Figure 3-1.

![Figure 3-1: Model Components (Singh, 1995)](image)

Most hydrologic and hydraulic models employ mathematical equations to simplify real world processes. The input and output of the models generalizes the behaviour of the system model that must reflect the real world system behaviour. Model can be further to describe the processes in the system, in this study, flow in river systems, overland and floodplain interaction.

3.1.1. System Characteristics

For floodplain modelling, one must have *a-priori* understanding on the heterogeneity exists on the floodplain. The characteristics of a floodplain comprise both natural and man-made features. Examples of natural features include the weather, climate, topography, soils and land cover. The basis for how the flood water would propagate on the floodplain is governed by combination of these features such as the amount of precipitation or water fallen within the system, the topography of the study area, which influence the flow rate as well as direction of the flow, the soils holding capacity and resistance caused by the land cover. The man-made features are urbanization, channelization, change in land use and water storage among many other features. The introduction of all these man-made features alter the flow rate, changes the surface water storage capacity, sedimentation rates as well as peak discharge and timing.
3.1.2. System Processes

Hydrological processes are spatially homogeneous though heterogeneity does exist in the real world. To incorporate all heterogeneity of a catchment in a model, some kind of assumptions and transformation on those data and processes must be introduced commonly so-called “effective” values. Arising from here it must be decided what scale will be suitable to meet the applications and thus the purpose of the study. This might requires some of the hydrologic responses treated as homogeneous. In this respect, Singh, (1995) describing that the scale should not be too small to be dominated by local features nor too large to ignore significant hydrologic heterogeneity and spatial variability of the catchment.

For the purpose of floodplain modelling, data needed are hydrologic data such rainfall, water level, discharge, information on the land use, geomorphologic data such as the river networks, drainage areas and most important of all is the digital elevation model. One major difficulty encountered for any modelling particularly in flood modelling is lack of adequate flood data and observations during the flooding events (Bates and De Roo, 2000).

In distributed hydrological models the spatial heterogeneity of catchment characteristics is usually discretized into small area elements which are considered homogeneous. Physically based models are in most cases only applicable in micro scale. As a result “effective” parameters are needed to calibrate these models to real world conditions.

3.2. Two Dimensional Model Description

The methods for mapping flood extent are ranging from simple such as by intersecting a planar observed water level surface with a digital elevation model of certain resolution and assigned to as flooded area (Priestnall et al., 2000) to highly sophisticated such as hydrodynamic modelling approaches as listed in Table 3-1. It is mentioned here that when the model grows in its complexity, more data are required for the parameterization.

<table>
<thead>
<tr>
<th>Approaches</th>
<th>Models</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Storage Cell</td>
<td>FLOODSIM</td>
<td>• Floodplain is discretized as inundation cells</td>
</tr>
<tr>
<td></td>
<td>LISFLOOD-FP</td>
<td>• Flow in main channel and between cells is described using uniform flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>equations – Manning or Weir formula</td>
</tr>
<tr>
<td>Small Storage Cell</td>
<td></td>
<td>• Floodplain derived from DEM either as raster or TIN</td>
</tr>
</tbody>
</table>
FLOODPLAIN INUNDATION SIMULATION USING 2D HYDRODYNAMIC MODELLING APPROACH
A CASE STUDY OF SUNGAI SARAWAK, SARAWAK, MALAYSIA

• Main channel is solved in 1D using either kinematic or diffusive wave model

1D hydrodynamic

HEC-RAS, ISIS, MIKE 11, SOBEK

• Solves 1D St Venant equation for series of cross sections of main channel and the overbank perpendicular to the main channel
• Spatial interpolation of water level in the 1D computational grid points into 2D inundation extent map

2D hydrodynamic

TELEMAC-2D, MIKE 21, DELFT-FLS, DELFT 3D

• Solves the full St Venant shallow water equations
• Discretization of floodplain and main channel using regular, TIN or curvilinear grid

Coupled 1D-2D hydrodynamic

MIKE FLOOD
SOBEK OVERLAND FLOW

• Solves the full St Venant shallow water equations for floodplain flow.
• Main channel is solved using the 1D approach

There has been much research work conducted with SOBEK. The model has been used with LiDAR data to study effects of DEM resolution in flood modelling (Alemseged, 2005), to map inundation extent for flood risk studies (Rahman, 2006). Examples of SOBEK applications in flood inundation modelling are shown in Table 3-2.

<table>
<thead>
<tr>
<th>Model approach</th>
<th>Study domain</th>
<th>Main Purpose</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D2D</td>
<td>377km² 13km long river reach Grid size 20 x 20m DEM derived from spot height</td>
<td>To map flood risk area in Liri Farigliano catchment, Italy</td>
<td>Frank, 2001</td>
</tr>
<tr>
<td></td>
<td>3300km² 60 km long reach Grid size 200 x 200 m DEM derived from spot height</td>
<td>To simulate flood and assess damage in Sistan Baluchistan River Basin, Iran</td>
<td>Dhondia, 2002</td>
</tr>
<tr>
<td>2D</td>
<td>78km² Varying grid size of 5m, 7.5m, 10 m were used DEM derived from</td>
<td>To simulate and assess flood hazards in Naga City, Philippines</td>
<td>Tennakoon, 2004</td>
</tr>
</tbody>
</table>
FLOODPLAIN INUNDATION SIMULATION USING HYDRODYNAMIC MODELLING APPROACH
A CASE STUDY OF SUNGAI SARAWAK, SARAWAK, MALAYSIA

<table>
<thead>
<tr>
<th>contour and spot height</th>
<th>To simulate the flood events with different return periods of floods in Lower Bicol floodplain, Phillipines</th>
<th>Usamah, 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D2D</td>
<td>• DEM derived from contour and spot height</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Grid resolution of 50m</td>
<td></td>
</tr>
<tr>
<td>1D2D</td>
<td>• DEM derived from LiDAR data</td>
<td>Alemseged, 2005</td>
</tr>
<tr>
<td></td>
<td>• Varying grid size of 5m, 7.5m, 10 m were used</td>
<td></td>
</tr>
<tr>
<td>1D2D</td>
<td>• DEM derived from spot height</td>
<td>Abdul Rahman, 2006</td>
</tr>
<tr>
<td></td>
<td>To simulate flood inundation based on different return periods and mapping hazards in Naga City, Philippines</td>
<td></td>
</tr>
</tbody>
</table>

Hydraulic flows models come in variety of forms have been employed to quantify flood magnitude and floodplain inundation (Bates et al. 1992, 1996, Marks and Bates, 2000, Alemseged, 2005, Abdul Rahman, 2006). A most commonly used hydraulic flow model is the 1-dimensional model that represented the channel flows. With more interest to model the flood inundation and extent, the use of 2-dimensional model is becoming more and more explored. Quite substantial numbers of literatures are available describing the use of 2-dimensional model with differences found in the type of spatial discretization used and varying level of complexity from simple diffusion wave approaches as used in Bates and de Roo, (2000) and D.Yu (2006a) and to solving full shallow water Navier-Stokes equations as described in Horritt (2000) and Beffa and Connell (2001). Apart from differences mentioned above, applications of 2 dimensional models have been diverse in its applications from river length ranging from 5-30km (Bates et al., 1996 and Connell et al., 1998) to the spatial resolution of the digital elevation discretized at 10–100m to represent the floodplain topography. Applications of high resolution digital elevation data derived from airborne laser to represent floodplain topography are still uncommon (Nicholas, 2003) although it has been attempted by Marks and Bates, (2000) at 11km floodplain reach in United Kingdom and Alemseged (2005) for 8km reach in Tegucigalpa City, Honduras. Obviously, there is some more room for further studies to be carried out using airborne laser derived digital elevation on a floodplain with complex channel and floodplain topography.

Since early application of 2-dimensional models are constrained in its utilities owing to lack of accurate representation of topographic elevation. Prior to the current state of art technologies in airborne remote sensing such as light detection and ranging (LiDAR), synthetic aperture radar (SAR) and various satellite imageries platforms traditional methods such as aerial photogrammetry, ground survey and analogue contoured maps are limited in the coverage areas constraint in time, cost and labours intensive. Nevertheless, over the last few years this situation has changed with more and more
accessibility to high end digital elevation data. Though LiDAR technology is considered to be still new to many countries due to its high costs but it would become the ‘in-thing’ in the future for collecting highly accurate elevation data and improve the way in updating the existing topographic data. Despite all the advantages of this system, it still cannot provide sufficient information of areas covered by water unless bathymetric or hydrographic sounding is employed. It is worth considering this limitation because in the case of flood modelling, it is utmost important to accurately represent river water surface level. To overcome this limitation, river cross section surveyed data is still a valuable source of information.

In this study, a physically based numerical model SOBEK 1D2D is selected. This model approach solves the full Saint Venant equations based on finite difference staggered grid solution. The floodplain is modelled using the two dimensional modelling approach described by three equations: the continuity equation, the momentum equations for the x and y directions as given below.

\[
\frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} + \frac{\partial h}{\partial t} = 0 \quad \text{[Equation 3-1]}
\]

In x-direction;
\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial h}{\partial x} + \frac{n^2 u \sqrt{u^2 + v^2}}{h^{3/2}} = 0 \quad \text{[Equation 3-2]}
\]

In y-direction;
\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial h}{\partial y} + \frac{n^2 v \sqrt{u^2 + v^2}}{h^{3/2}} = 0 \quad \text{[Equation 3-3]}
\]

with

\[
y = \text{depth of the channel from the reference level} \quad [\text{L}]\\
x = \text{longitudinal distance along the channel} \quad [\text{L}]\\
t = \text{time} \quad [\text{T}]\\
h = \text{water head elevation from reference level} \quad [\text{L}]\\
u = \text{flow velocities in x-direction} \quad [\text{LT}^{-1}]\\
v = \text{flow velocities in y-direction} \quad [\text{LT}^{-1}]\\
n = \text{Manning coefficients (dimensionless)}
\]

The numerical procedure for solving the above equations for the main channel and floodplain are described below using the Strickler Manning equation.

\[
Q = k_s A R^{2/3} S^{1/2} \quad \text{[Equation 3-4]}
\]
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A CASE STUDY OF SUNGAI SARAWAK, SARAWAK, MALAYSIA

with \( k_s \) = Strickler Manning coefficient \([L^{1/3}T^{-1}]\)
\( S \) = energy slope (dimensionless)

The representation of the dynamic processes can be illustrated using a grid cell model as shown in Figure 3-2. Firstly, the study area is schematized into regular grids at selected resolutions with \( \phi \) and \( Q \) represents the water level within the cells and fluxes across a cell boundary. Equation 3-5 shows that water level within a cell change over time as function of incoming and outgoing forces.

\[
\frac{\Delta \phi}{\Delta t} = \Sigma Q_{in} - Q_{out} \quad \text{[Equation 3-5]}
\]

Assuming that the flow transfer between the two grids cells occur along the \( x \) axis, the flows can either flowing out or in the cells depending on the difference in the relative water level surface. The change of water level a cell with space index \( i-j \) is calculated at each time step using the following equation. Discharge flows are describe by Equation 3-4.

\[
\frac{\Delta \phi^{i,j}}{\Delta t} = \frac{(Q_{in}^{i-1,j} - Q_{out}^{i,j})}{dx} \quad \text{[Equation 3-6]}
\]

For each time step the sum of the fluxes into and out of the each cell are calculated according to the water surface level in each cell at the start of the time step. The water level at a grid cell represents average depth over whole cell. By the distribution of hydraulic heads across the model domain, water will diffuse across the domain.

### 3.2.1. Boundary Conditions

In floodplain modelling, it is crucial to properly describe the boundary condition. Boundary condition plays a role as a connecting node that defines flux relationship between the model domains area and its
surrounding area. Boundary condition needs to be defined at the upper and lower boundary of the model domain area can be represented by either series of constant discharge, Q or series of water level, H (as a function of time). A wrong choice for boundary conditions may generate a misleading water balance of the system and consequently resulted in serious propagation of errors throughout the simulation, thus giving ambiguous results.

In hydraulic and hydrologic modelling, in general there are three types of mathematical boundary conditions namely:
1. Dirichlet condition - specified head boundary,
2. Neumann - specified flow boundary and
3. Cauchy condition - head dependent flow boundary.

In Dirichlet boundary condition, the hydrological state of a specified hydraulic head is described as $h(x,y,z) = h_0$, with $h_{(x,y,z)}$ is the constant head boundary at location $x$, $y$ and $z$ and $h_0$ is the specified head value defined as a function of time.

In hydrologic modelling, Neumann boundary condition gives: $q_x = \frac{\partial h}{\partial x}$, the specified flow boundaries is constant across the boundary. The examples of specified flow boundaries in hydrology are the flow to surface water bodies, the natural groundwater recharge and infiltration to unsaturated zone.

Neumann boundary condition is applied to zero flux boundaries such as at water divide of a catchment, impermeable fault zone, sharp boundary between fresh and salt water in a coastal aquifer and streamlines on a cross section perpendicular to the contour lines of the hydraulic heads. Cauchy boundary condition is dependent upon the difference occurred between the specified head outside the model boundary and the calculated head inside the model boundary.

### 3.2.2. Surface Roughness

For the purpose of flood modelling, roughness coefficients need to be defined for natural rivers and floodplains. Usually, the roughness coefficients (Stricker Manning, $k_s$) cannot be measured directly and therefore needs to be estimated. As an empirical parameter, the roughness depends on several factors such as small scale topographic heterogeneity, vegetation characteristics and channel geomorphology.

Usually, the value of roughness parameters is estimated through a trial and error model calibration procedure that is based on visual comparison of simulated and observed values. This approach is subject to uncertainty and also time consuming.

Cobby et al. (2003) also has used LiDAR data sets to analyse different properties of floodplain vegetation features such as trees and hedges that effect surface roughness. Mason et al. (2003) has
reviewed few approaches to measure vegetation height data and transformed this information into roughness coefficients over the floodplain.

In urban areas, DEM represents two aspects that are the ground and also the buildings. For application in urban area, it is needed to separate the buildings from the ground. Maas and Vosselman (1999) presented algorithms to segment buildings roofs. However, the approach was not attempted in this study but just focuses on extracting the whole surface landscape.

3.3. Model Calibration

Calibration is a process of fine tuning a model by optimizing the model parameters by modifying the model structures, boundary conditions and improving the hydro meteorological forcing input. Extensive calibration in this study was not undertaken because due to time constraints. Optimization of the parameter value is done manually and checked qualitatively such as by plotting of observed and simulated water level outputs. The other method is quantitatively such as residual statistics of Root Mean Square Error (RMSE) or Bias. Calibration of a model by comparison of observed and measured distributions is not an easy task. It requires careful consideration of the overall comparison, maybe not to the extreme of point comparison depending on the purposes and objective to be achieved.

Performance measures are quantitative indicators of how well or poorly an alternative meets a specific objective. Feature of good performance measures are:

- Quantifiable
- Have a specific target
- Indicate when the target has been reached or
- Measure the degree of improvement towards the target when it has not been reached.

Performance indicators are in contrast to performance measures. It does not have specific target but are used to provide an indication of the relative behaviour of the alternatives.

The objective of the calibration is to adjust some model parameters such as to decrease the difference between the observed and the simulated water level values. In this study, calibration was done both qualitatively and quantitatively using the objective functions as listed below:

1. The Root Mean Squared Error (RMSE)

The RMSE is the standard deviation between the measured and calculated head water and is represented with the following equation:

$$RMSE = \left[ \frac{1}{n} \sum_{i=1}^{n} (h_{measured} - h_{calculated})^2 \right]^{0.5}$$

... Equation 3-7
Root Mean Square Error (RMSE) in flood modelling indicates the accuracy of flood extent as flood water propagates. This measures the discrepancy between the modelled and observed values on an individual basis and indicates the overall predictive accuracy weight is given to larger discrepancies. With this measure, smaller values indicate better model performance.

2. Nash Sutcliffe

\[
NS = 1 - \frac{\frac{1}{n} \sum_{i=1}^{n} (O_{\text{simulated}} - O_{\text{observed}})^2}{\frac{1}{n} \sum_{i=1}^{n} (O_{\text{observed}} - \overline{O}_{\text{observed}})^2}
\]  

Equation 3-8

With this coefficient, values equal to 1 indicate perfect fit between observed and predicted data, and values equal to 0 indicate that the model is predicting no better than using the average of the observed data. Therefore, positive value above 0 suggests that the model has some utility, with higher values indicating better model performance.

3. Bias

\[
\%Bias = \frac{\sum_{i=1}^{n} (h_{\text{measured}} - h_{\text{observed}})}{\sum_{i=1}^{n} h_{\text{observed}}} \times 100
\]

Equation 3-9

Where \(x\) is the observed value, \(y\) is the model simulated value and \(n\) is the number of observations. Bias values closer to zero indicate better overall model performance.

3.4. Overview of LiDAR Technology

LiDAR has gained considerable acceptance as a new technique to map topographic surfaces on top of conventional methods such as aerial photogrammetry, land surveying and contour digitization. In addition to providing a characterization of ground topography, LiDAR data sets that come in multiple returns give new knowledge about surface roughness, vegetation parameters and buildings structures. LiDAR currently available are in a fairly mature state of art, while the processing of LiDAR data sets is in an early phase of development (Axelsson, 1999). The LiDAR data was processed to generate digital elevation model (DEM) which later applied in many hydrological/hydraulics and environmental applications such as in floodplain inundation modelling, riverbank elevation for flood management, forestry mapping and monitoring urban area density and change detection.
For most of the applications mentioned, it requires certain accuracy limit. Reportedly, LiDAR can provide a high quality DEM with precision within $\pm 25$ cm depending on the surrounding environmental conditions such as the land cover, slope and also the LiDAR system parameter such as the flying height (Kraus et al. 2003). Specific for the purpose of hydrologic modelling, there are many literatures available describing the use of LiDAR data. For the purpose in flood modelling, (Cobby and Mason, 2001) mentioned that LiDAR is capable of producing vertical accuracy of 15–20 cm and 0.5m horizontal accuracy.

Topographic LiDAR systems have several limitations such as it does not penetrate through certain features such as water surface or areas covered with water and even clouds. These features tend to absorb the laser scanner pulses especially in the near infra-red region. Bare earth elevations are effected by features such as buildings, bridges, culverts, and dams. In literature it is also reported that forest, grass and mashes can produce false bare earth elevation data. The logistic management and processing of LiDAR data requires sufficiently high end computational and storage capabilities. Post processing removes questionable returns resulting in irregularly spaced points and sometimes large areas with no data.

Despite these limitations, LiDAR has widespread advantages over many traditional photogrammetry techniques. The data collection is considerably cost effective, timely efficient as the data can be generated almost immediately after the flying campaign. The spatial area of coverage is also larger and contains high precision and high density point data. Certainly, this has overcome the limitation of traditional methods for ground observations and data collection that are time consuming and resources extensive. Furthermore, LiDAR can either be flown at day and night or cloudy or rain.

### 3.5. LiDAR operating principles

LiDAR is an acronym for Laser Imaging Detection And Ranging. Other term for LiDAR which is widely used in many literatures includes airborne laser altimetry, airborne laser scanner and ALSM (Airborne Laser Swath Mapping). All these terms refers to the same principle which measures properties of scattered light to find range and/or other information of a distant target.

LiDAR system consists of three basic parts which are the laser scanner, the airborne and ground based Global Positioning System (GPS) and the Inertial Measuring Unit (IMU). The laser scanner mounted in an airborne platform, sends out narrow pulses towards the ground (such as buildings, vegetations, roads etc) and reflected back to the sensor when pulses hit the objects or the ground. Combining the laser range, laser scan angle, position from the GPS and orientation of the aircraft (pitch, yaw and roll) from the IMU, accurate ground coordinates of $x$, $y$ and $z$ positions are obtained for both natural and man-made features.
The LiDAR scanner scanned all objects that include residential houses, buildings, vehicles, highways and railways, all telecommunication lines, dense trees, vegetations, agricultural farms as well as the earth ground itself. In urban areas, stretches of roads are sometimes partly covered by high trees canopy. As shown in Figure 3-3(b) the laser scanner will read the top or the lower branches of the trees as the first pulse return. The last pulse return will records point on the roads. For many topographic purposes, the last returns are useful for further generation of digital elevation models (DEM). At this stage, it is necessary to separate the non-ground and ground points. The size of individual vehicles and trees are much less than that of buildings, so most of them are removed during the filtering process (Figure 3-4).
Figure 3-3: (a) Schematic illustration of LiDAR system (Bakker et al.1999) (b) First and Last Returns

Figure 3-4: (a) First Pulse Return and (b) Last Pulse Return point measurements for sample area with identified Buildings, Trees and Roads.
4. MATERIALS AND METHODOLOGY

4.1. Data Availability

During the fieldwork exercise in September 2006 several secondary datasets were collected. The list of data collected is shown in Table 4-1. In this study, GIS software ArcGIS 9 and Erdas Imagine were extensively used for the processing of various spatial data layers required for the modelling.

<table>
<thead>
<tr>
<th>Remote Sensing Data</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topographic LiDAR data</td>
<td>True Height Value</td>
</tr>
<tr>
<td>Data</td>
<td></td>
</tr>
<tr>
<td>Historical Flood Maps</td>
<td>Shape File</td>
</tr>
<tr>
<td>Water Level Data (Hourly, Monthly, Yearly)</td>
<td>Excel Table file</td>
</tr>
<tr>
<td>Rainfall Data (Hourly, Monthly, Yearly Records)</td>
<td>Excel Table File</td>
</tr>
<tr>
<td>Sg Sarawak River Cross Sectional Data</td>
<td>CAD File</td>
</tr>
<tr>
<td>Kuching Roads Networks Layers</td>
<td>Shape File</td>
</tr>
</tbody>
</table>

4.1.1. LiDAR data sets

The LiDAR data used in this study were collected in January 2006 using an Optech ALTM 2050 LiDAR system over an area of approximately 400 km$^2$ (Figure 4-1). The ALTM 2050 is a high resolution discrete measuring system that gives two returns – first and last pulse respectively for each height points. The LiDAR data has a resolution of 1 m. The manufacturer quoted accuracies of the Optech 2050 LiDAR system flying at 1067m above ground are as follows: an elevation or vertical accuracy of $\pm 0.15$ cm and horizontal accuracy of $\pm 0.5$ cm. The other specifications are given in Table 4-2.

The point density on the ground is reported to be about three or four height points per 1m$^2$. The mission was designed with up to 50% side overlap to increase the point density on the ground. The resulting three dimensional coordinates were compiled in an ASCII mass point file of x, y and z with the BRSO projection and Timbalai 1948 Datum for each of the laser returns.
In this study, the LiDAR data was already separated into ground and non-ground point files. Since it is quite a large area, the dataset contained over millions of LiDAR point data, it was divided into smaller tiles of 1 by 1km to make up the entire study area.

**4.1.2. Sg Sarawak Water Level Stations**

Six water level stations within the study domain of Sg Sarawak where data are recorded in hourly interval are gathered and analysed. Figure 4-2 shows the location of the water level stations utilised for
this study. For the purpose of this study, water level station at Batu Kitang was used to provide a continuous water level records. Few other water level stations within the study domain were also used to provide water level information. Recorded water level data within Sg Sarawak during the period of 1st – 8th February 2003 was selected for simulation are shown in Figure 4-2 below.

Water levels at few gauging stations along the Sg Sarawak were selected for the purpose of upstream and downstream boundary conditions to be applied in the model. Figure 4-5 shows the time series of discharge during the 2003 flood.

4.1.3. Sg Sarawak River Cross Sectional Information
The longitudinal sections of Sg Sarawak Kanan and cross sections are shown in Figure 4-6. The bed levels at Batu Kitang is at RL -3.5m LSD whilst at the river mouth of Sg Sarawak some 50 km away bed levels are at RL-12.0 m LSD. A total of 108 river channel and floodplain cross sections were
available for Sg Sarawak. For the main river, especially at the downstream of Sg Sarawak, the river cross sections were surveyed at an interval of every 500 meter whereas, in the upper stream the surveyed interval was at 1000m to 4000 m.

(b)Figure 4-3 : (a) Sample cross section at Batu Kitang (b) Longitudinal Profiles for Sg Sarawak as derived from surveyed cross sections (Source: DID

2 Department of Irrigation and Drainage

4.1.4. Historical Flood Information

Data is lacking in accuracy and might not really reliable for the purpose of the whole study as there is no systematic or appropriate collections during those flood events. Reportedly, some water level
stations were malfunction during the course of the flooding. Even there are telemetry stations available at the department, it is reported that these give unreliable reading during this periods due to disruption in electric supply or the recorders were run out of battery and unable to transmit the data back to the main system³.

However, several information were collected during and after the events through taking high water marks at the buildings walls, photographs taken during the events, unpublished personal communication with the locals and extracted information from the damage reports.

The digital flood extent map for the flooding in February 2003 was available together with coarse information on the depth of flooding. Few recorded water levels at stations along the river of Sg Sarawak also available for comparison. A collection of photographs from local newspapers were also available to show the degrees of the flooding at certain areas within the floodplain.

![Figure 4-4: Photographs showing the field surveyed during the flood February 2003 and aerial photograph over part of the study area](image)

4.2. Softwares and Hardware Used

4.2.1. Softwares

- SOBEK
- Erdas Imagine 8.7
- ArcGIS 9.1
- Microsoft Office XP (Words, Excel, Visio, Power Point)

4.2.2. Hardware

- Pentium IV, 3.20 GHz processor with 1 GB RAM

³ Some paragraphs in this thesis are intended to explain what cause the unavailability of continuous data. This description is one of them.
4.3. Methodology

4.3.1. LiDAR DEM Generation

The aim is to produce an elevation model that best represents the topography within the study area. In this study, the LiDAR data was already separated into ground and non-ground point files. Since the first pulses return corresponds to features such as buildings and trees, this file was used to produce digital surface model (DSM). In contrast, the last pulses return corresponds to the ground return was used to produce digital elevation model (DEM).

A total of 160 tiles of 1 km$^2$ containing last pulses return were converted from ASCII data to point shape format in ArcGIS. Each layer contained dense points at minimum of 150,000 points per square kilometre. The tiles were merged to form a single layer containing x, y and z point map. Then the points file were interpolated using inverse distance weighting (IDW) method to produce a ‘bare earth’ raster DEM. IDW method is based on the assumption that the interpolating surface should be influenced mostly by the nearby points and less by the more distant points. The interpolating surface is weighted average of the scattering points. The weight assigned to each scattering points diminishes as the distance from the interpolation point to the scattering point increases. Since IDW is a weighted average method, no cell receives a value that lies outside the range of the minimum and maximum of sample points.

Figure 4-5 : LiDAR ASCII data and points shape files

For the purpose of modelling in this study, a low pass filter of 3 by 3 focal mean neighbourhood was applied to raster DEM. This filter reduces any local variation and removes noises in the raster DEM. The generated raster DEM will be smoothen. Subsequently, raster DEM were resampled and mosaiced to form the 20 m grid resolution raster DEM.
River cross section data is used to characterize the flow carrying capacity of the river. Digital copy of the surveyed river cross sections information were converted from CAD drawing format to ArcGIS to get the point location of the surveyed area and also spot height of the river bed. The distance between two cross sections was selected at 500 m and points with cross sections at interval of 1m each. These points were then interpolated using inverse distance weighting to generate a GRID.

The sample cross section from the CAD drawing was extracted to show actual river bed cross sections.
Figure 4-7 illustrated the LiDAR raster DEM with location of the grid representing the bank top of the river channel as shown in (ii). In the raster DEM, grid representing the channel was not representing the actual riverbed. Therefore, these elements were extracted and replace with the grid interpolated from the surveyed river cross section points [Figure 4-5]. In the raster DEM, riverbed and also near channel areas should correctly represented as shown in (iii). The river cross sections topography [Figure 4-6] giving a trapezoidal cross section extended to the floodplain.

Figure 4-8: Illustration of LiDAR raster DEM

Figure 4-8 showing the final raster DEM after drapped with the river bed information.

Figure 4-9: Illustration of the LiDAR raster DEM and cross section
Figure 4-10: Final raster DEM for the study domain
4.3.2. Model Setup

SOBEK 1D2D model developed by WL/Delft Hydraulics, the Netherlands was selected for application in this study. The model solves the full Saint Venant equations based on finite difference staggered grid schemes shall involves the calculation of flow magnitude between two adjacent cells according to the difference in water level surface and Strickler Manning equations.

Figure 4.8 illustrates schematically and conceptually the components of the floodplain to be modelled within SOBEK Network Editor – NETTER, a platform for pre and post processing of data. NETTER requires the input geometric data to represent river networks, river cross sections, calculation points, connection nodes, boundary lines, boundary nodes and digital elevation model represented in 2D grid. Roughness coefficient is indicated by Strickler Manning, $k_n$ coefficient single values for floodplain.

In representation of floodplain and river channel topography, an ASCII file for the raster DEM with computational domains of 1012 and 785 grid elements was imported into the SOBEK NETTER. The model boundaries were defined at Batu Kitang and Satok with recorded water levels varying in time sets as the upstream and downstream boundary conditions respectively. Having schematized the model, it is important to initialize water level for the full simulation. The program will automatically fill up the river channel up to the specified water level and starts the simulations from this level onwards. Initial computation time to reach the initial water level is referred to as ‘restart file’- which later will be used to the actual simulations.
Actual simulation is for the flood event starting from 31 January to 7th February 2003 and considered the rise and fall of the water level within the system. Model computational time steps of 60 s were chosen being time steps are automatically adapted based on calculated flow characteristics. Roughness coefficient of 0.035 was applied for the floodplain specified based on general land use within the study area. This is adopted after Tennakoon (2004) and West Sacramento (2002).

<table>
<thead>
<tr>
<th></th>
<th>Roughness Coefficient [Source: Tennakoon, 2004, West Sacramento, 2002]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads</td>
<td>0.025</td>
</tr>
<tr>
<td>River</td>
<td>0.030</td>
</tr>
<tr>
<td>Commercial Zones</td>
<td>0.032</td>
</tr>
<tr>
<td>Residential Areas</td>
<td>0.035</td>
</tr>
<tr>
<td>Agricultural Zones</td>
<td>0.040</td>
</tr>
<tr>
<td>Buildings footprints</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Figure 4-12 illustrates schematically and conceptually the components of the floodplain to be modelled within SOBEK Network Editor – NETTER.

Figure 4-12 : Schematization of the floodplain
The following are the output parameters as pre-selected in the SOBEK.

Discharge at section: showing the discharge through a cross section at a particular time. The results on is a hydrograph at that section.

History Station: showing the history of the calculated water levels save for each time step of the simulation.

Quantities in map files: showing the pre-selection of the map files saved during the simulation such as water depth, (H), flow velocity, (C ), water level (Z) and velocity components (u and v).

Video Animation: showing the incremental water depth or velocity
5. RESULTS AND DISCUSSIONS

This chapter presents the results and discussions on the outputs. Firstly, reviewing the types of assumptions made to the data and methodology applied to process the data. Then, the simulations outputs for the February 2003 flood event.

Many factors can affect the accuracy of the flood simulations: input data, initial condition, boundary conditions, model assumptions, parameter values and digital elevation spatial resolution. Model error results in the inability of the flood model to predict inundation accurately, even given the correct estimates and input. Model error will always be a factor since no model can represent the real world system exactly.

5.1. Flood Inundation

Figure 5-1 shows the simulated flood inundation spatial extent with flood water depths. The simulated flood extent is the maximum extent of the flooded area with flood water heights as observed on 5th February 2003.

Figure 5-2 showed the flood extension as surveyed during the flood by the Department of Irrigation and Drainage, Sarawak. By comparing the simulated results with the surveyed flood extent, it can be concluded that simulated results is close to the actual situation. It is noticed that the area inundated from the simulation is larger than actual situation and mostly concentrated along the river.

Figure 5-3 showed the timing of flood water height at Sg Maong, Satok and Desa Wira during the flood period starting 1st February till 5th February 2003.
Figure 5-1: Simulated flood inundation extent and flood water height with snapshots of photographs taken during the flooding

Figure 5-2: Observed Flood Inundation extent as surveyed by DID
### Figure 5-3: Flood Timing for maximum water height for the observed and simulated flooding event at Batu Kawa, Batu Kitang, Sg Maong, Satok and Desa Wira

From the results, it shows that the model simulated flood inundation extent agree well with the observed inundation extent. Despite the fact that the model was not well calibrated, the simulated results with appropriate input data, initial condition, boundary conditions, assumption applied to the model, roughness coefficient values and coarse representation of the grid resolution were able to generate a presentable simulated flood inundation extent.

Therefore to assess the above results further, model performance indicator analysis were applied to the simulated results.
5.2. Model Performance and Calibration

The purpose of performing model performance was to compute a numerical measure of the difference between the simulated and observed. In respect to this, in this study, the following performance statistics were used to measure the difference.

The observed and simulated water heights were shown in Table 5-1.

<table>
<thead>
<tr>
<th>Water Level Stations</th>
<th>Observed</th>
<th>Simulated</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maong</td>
<td>6.75</td>
<td>4.35</td>
<td>-2.40</td>
</tr>
<tr>
<td>Desa Wira</td>
<td>3.70</td>
<td>2.50</td>
<td>-1.20</td>
</tr>
<tr>
<td>Satok</td>
<td>2.15</td>
<td>3.55</td>
<td>1.40</td>
</tr>
<tr>
<td>Batu Kawa</td>
<td>3.40</td>
<td>4.60</td>
<td>1.20</td>
</tr>
<tr>
<td>Batu Kitang</td>
<td>3.38</td>
<td>2.50</td>
<td>-0.88</td>
</tr>
</tbody>
</table>

The results based on Equation 5-1 to 5-2 are as listed below:

<table>
<thead>
<tr>
<th>Statistics Performance Indicator results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Simulated</td>
</tr>
<tr>
<td>Average observed</td>
</tr>
<tr>
<td>% Bias</td>
</tr>
<tr>
<td>RMSE</td>
</tr>
<tr>
<td>Nash Sutcliffe</td>
</tr>
</tbody>
</table>

The aim in calibration is to adjust the model parameters to decrease the difference between observed and simulated water level values. The closeness of fit can be checked qualitatively (e.g. plot of observed and simulated) or quantitatively (residual statistics such as Root Mean Square Error, Bias and Nash Sutcliffe).

Overall, it is shown that SOBEK 2D is successfully applied and capable of simulating and providing accurate inundation extent for a large study area (>130km²) such as in this study. Despite the facts that the model was not calibrated, the simulated results showed that with appropriate input data, initial and boundary conditions, model assumptions, empirical roughness coefficient values and coarse representation of grid resolution were able to generate a presentable simulated flood inundation extent. However, caution should be used in interpreting the results of this study considering all the underlying assumptions made to the model. Horritt and Bates (2001) highlighted that there interrelated importance in the input data, process representation and model validation.
5.3. Assumptions made in this study

In this respect, Rientjes (2006) has highlighted few modelling protocol need to be clearly understood prior to do any kind of watershed modelling. The person needs to be clear on the objective of the model and what is the model intended for. Related to this, few fundamental questions need to be addressed such as:

1. What is the application of the model?
2. What specific questions do you want the model to answer?
3. What complexity is warranted?
4. What data is available?
5. Is a modelling exercise the best way to answer the questions?
6. If, yes, what mathematical model is needed?
7. How the model should be approach?

As discussed earlier in Chapter 3, hydrological processes are spatially homogeneous though heterogeneity does exist in the real world. Therefore, some kind of assumptions and transformation must be introduced to incorporate all these heterogeneity of a catchment in a model.

Several assumptions were made in the model used in this study. Assumptions include the degree of uncertainty that associated with the model results due to the choice and the effect of generalisation of input data and how it affects the outcomes. These assumptions contribute to the overall uncertainty present in the results. To provide error free results is least impractical and in reality impossible. For that reason, most practical approach for any modellers is to make the model, data and error assumptions explicit to decision makers.

5.3.1. Hydrological Processes

In this study, a physical based numerical model approach was used to solve numerically the real world processes based on full Saint Venant equations using finite difference solution grid. Real world are continuous in space and in time. In modelling, the spatial representation of real world is based on discrete sampling and discretized on a grid for the representation of the land surface processes. Seyfried et al. (1995) mentioned that among the many problems encountered with physically based model is the difficulty in parameterization, validation and representation of land surface processes on a grid.

In this model, two boundary conditions need to be specified, one at the upstream and downstream of the study area. Lacking in direct and continuous measurement upstream

Only those processes of interest are going to be considered. Saint Venant equation contained information for the description of topography, geometric and hydraulic characteristics of the system to be modelled.
5.3.2. Digital elevation model processing

The raster DEM serves as a basis for flood modelling and flood inundation prediction. The raster DEM processing is subject to error and uncertainty and results in a raster DEM that does not perfectly match the real world elevations. Small differences in values in the DEM used as input into the flood modelling can lead to a large effect on the overall predictions. The concern arises for the quality of the generated DEM and the choice made for grid spatial resolution. The effects of such choice for determining accurate flood inundation extent and flood water depth should be further research.

The effects caused by these differences have been discussed in many literatures such as Haile (2005), Kates and Marks (2000), Bates and de Roo (2000). Despite these noted differences, it is of course impossible to comment on which predictions closest to perfect be used. Clearly, if these models were to be used in the quantification and mapping of flood risk areas, the use of different processing techniques could substantially alter the results. This same argument holds for the use of the DEM in a similarly sensitive application such as flood wave propagation modelling.

The introduction of errors in the processing of the data remains only one source of error in the process of modelling using LiDAR data. Whilst differences interpolation methods have been highlighted in many literatures, it should be noted that there is no optimal creation of methodology, as the final decision regarding interpolation methods, grid spacing, filtering methods must be driven by the requirements of the applications for which the DEM is intended for. The uncertainty in the generated raster DEM considered results from the method of interpolation that used is to generate the raster DEM.

5.3.3. Land surface roughness parameterization

The model used in this study requires the specification of surface roughness coefficients. An effective spatial surface roughness coefficient of 0.035 was used based on empirical roughness coefficient value specified in Tennakoon (2004). At this point, it is necessary to emphasize that little were known about surface roughness coefficient that are meaningful for urban areas. In this model, the topographic heterogeneity within the study area was averaged out and represented explicitly in the grid resolution of 20 x 20m. In urban areas, structural features such as buildings, roads and trees can have a considerable effect on the flow directions and timing. The simulation in this model is not attempting to calibrate the results with different roughness coefficient. Despite the use of high resolution LiDAR data in this model, many areas such as deriving land surface roughness was not treated well. One of the major problems is due to complex topography in urban areas. Perhaps the implication of this choice of a simple treatment of the land surface properties has reasonably give effects on the flooding inundation extent.

LiDAR is capable of producing topographic heights at a vertical accuracy commensurate with and at spatial resolutions as required by the flood model (Cobby et al, 2001). Reconstruction of surface objects such as buildings is often difficult by inadequate sampling (Maas and Vosselman, 1999). For
determination of object friction, full reconstruction is unnecessary and we require only the object height from the LiDAR data. A typical rural floodplain environment will contain mainly vegetation covers including grass, crops and small houses and roads.

For the purpose of further studies, need to conduct sensitivity analyse for the surface roughness incorporating the consideration of scale and spatial heterogeneity. Recent studies of D.Yu (2006a) suggested the proper selection of roughness coefficient should not only depend upon the system being modelled but most importantly the grid resolution that being used to discretize the model mathematical equations. In his studies, he found that roughness coefficient is sensitivity is in direct relation to grid resolution.

Much of 2D modelling has focused in rural areas. In this respect, Wheater (2002) has suggested an improved representation of urban flooding at both the local and catchment scale to reflect the highly variable pattern of flood propagation on the floodplain.

5.4. Limitations in this study

It is important to address the major limitations in this model because most of the unresolved limitations stem from the simplifying assumptions that were made in the setup and apply the methodology at the scale of the whole floodplain in the study area. At this scale, the complexity of the floodplain processes has not been represented in detail. All these process complexities have been simplified in order for it to be applied on such a large scale.

5.4.1. Model Setup

Several problems were encountered during the schematization and setup of the model. As an input into the NETTER, raster DEM file need to be converted into ASCII file format with a specified header.

The raster DEM is in ESRI binary raster floating file format and associated with “.aux” files that stored the statistical information, coordinate system and projection information about the raster file. To make the conversion, the raster DEM need to be read in ArcToolbox with a conversion tool command Raster to ASCII. The output of this operation is the ASCII file consists of header information containing keywords followed by cell values as shown in Figure 5-4 (a).

In any 2 dimensional modelling, the most important input is the 2D grid. During the schematization in NETTER, the first thing to do is to import the 2D grid. This .ASC file should have exactly the same format including number of columns and rows as the height definition file. It is necessary to check and make some minor fix to the ASCII file as this might trigger error during simulation. It is necessary to re-aligned all columns and rows as in the manner shows in Figure 5-9 (a) and (b) respectively.
As mentioned in the SOBEK HELP, number of elements in the grids determine the simulation time. The fewer elements there are, the shorter the simulation takes. SOBEK has been tested with few ranges of maximum 2D grid elements that can be used for simulation. Therefore SOBEK was recommended for element sizes of around 360,000 for efficient simulations tasks. All this experiment was simulated using Windows 95 computer with Pentium II 450 MHz processor and 128 Mb of RAM.

<table>
<thead>
<tr>
<th>Number of element in grid</th>
<th>Calculation time per 1 min time step</th>
</tr>
</thead>
<tbody>
<tr>
<td>170,000</td>
<td>16.5 second</td>
</tr>
<tr>
<td>360,000 (600 x 600)</td>
<td>25 minutes</td>
</tr>
<tr>
<td>490,000 (700x 700)</td>
<td>Caused problems in the post processing</td>
</tr>
</tbody>
</table>

In this study, an ASCII file for the study domain was made up of 794,420 elements of raster DEM 20 x 20 m grid resolution. From the number of elements it was already large and this affected the calculation time. For the selected time step, the calculation time for the whole area takes 2-3 days.

An attempt was made on the 10 x 10 m grid resolution that contained 3,177,680 elements. Obviously, SOBEK was unable to handle this size and resulted in the SOBEK to crash on the parser2d.exe flow program files and fails to finish the tasks.
Therefore, it is concluded that although SOBEK is very robust modelling software, it still has limitation. In this respect and before attempting any modelling, it is recommended to choose a coarse grid when accuracy of the results is not critical. Although it is possible to specify multiple grids resolution within one case, this configuration was dropped in the current version of SOBEK.

### 5.4.2. Effects of selected boundary conditions

The availability of appropriate spatial data remains is of major importance in any modelling. It is very often that data sources are available but at different resolution. In order to put all the data in a common scale, it is necessary to make some kind of assumptions and transformation on those data to so-called “effective” values. The observed scale of input data is transformed so that the input physical parameter can be uniquely represented in a defined model scale. Effects of boundary conditions are note further explored. Following Alemseged (2005) however, shows effects of selected boundary conditions do not propagate into the model domain.

### 5.4.3. Effects of land surface roughness

One of the main limitations in this model is the difficulty in specifying the complex variation in the urban areas topography and its roughness characteristics. In practice, matching the numerical model setup with the real world properties is not possible. As such, a correct estimate of the surface roughness is needed to model the urban properties.
5.4.4. Effects of river geometry

Another input that could lead to some inaccuracy in this study are river cross sections, although the river cross sections were obtained from ground survey. The river cross sections were surveyed in 2000, the flood occurred in 2003 and the LiDAR was collected in 2006. In between these years, probably of changes in the cross sectional flow area could be observed due to sedimentation along the river reach. Another possibility that could lead to some uncertainties in the results is the representation of the river cross section in the raster DEM. The LiDAR was taken in 2006 therefore again; some changes after the occurrence of 2003 might have taken place along the river banks. Timing synchronization between time of surveying and collection of the LiDAR data are very far different.

Besides timing, the interpolation method that was applied to the river cross sections point might have generated errors. IDW method was also selected in the interpolation of these points into a raster GRID that later was draped onto the raster DEM. This might have introduces some small edges errors between the river channel and also the floodplain. So for this reason, large variation exists in elevation of the actual river bed and elevation of the floodplain.
6. CONCLUSIONS AND RECOMMENDATIONS

This chapter discusses conclusions that can be drawn from this study and presents some recommendations for further research.

6.1. Conclusions

The applicability of using LiDAR data sets is put to test over Sg Sarawak catchment by applying it in hydrodynamic model SOBEK 2D, which is already operationally feasible for flood inundation modelling in many areas. Since SOBEK 2D is successfully applied in many flood studies and proved to be capable of simulating and providing accurate inundation extent for a large study area (> 130 km²), the model approach has been selected.

Specific conclusions are summarized as below.

a). Despite the facts that the model was not calibrated, the simulated results showed that with applied input data, initial condition, boundary conditions, model assumptions, empirical roughness coefficient values and coarse representation of grid resolution, the approach was able to generate a simulated flood inundation extent that approximated the observed extent of February 2003. Also data on flood characteristics such as extent, timing and propagation was rather sparse and further constrain on accurate calibration. Conclusively, there is a requirement for a collection of suitable and better field gauging station records to validate this model as this helps in determining the relative impacts of model parameters and physical hydrological processes on the flood wave propagation.

b). While model simulated results match reasonably well with observed data, caution should be exercised in interpreting the results of this study. Model performance indicators is used to provide a more definitive results of the simulation results

c). It is expected that simulation results could be reasonably improved if information such as buildings, vegetations, trees, hydraulics structures within the river channel could be included in the model schematization. Cobby et al. (2003) and Mason et al. (2003) have derived methods that could be used for the derivation of surface roughness from the vegetation height, type and density. Haile (2005) and Shorma (2005) in their studies also have used methods to extract and represent buildings from LiDAR and subsequently for use in hydrodynamic modelling. However, due to time constraints, it was not possible to effectively carry out suggested methods during this study.

d). Since it is impossible to abstract channel bed cross section from digital elevation model, such must be obtained from other sources such as from field surveys. Channel cross sectional area needed to be joined to the floodplain DEM by raising or lowering the channel sections until the river banks levels coincide with the DEM levels. This will ensure that the channel and the floodplain have a consistent datum.
6.2. Recommendations for future research

By this study the followings recommendations can be made:

1. This study was performed with a 2 dimensional flood model. It is worthwhile to extend the modelling approach to simulate urban flooding that also incorporate the local drainage networks, man-made structures such as houses, roadways, bridges and embankments to accurately simulate the complex flood water flow paths in this complex situations.

2. It is strongly recommended to further explore the utilisation of the LiDAR data to improve in the parameterisation of the land cover roughness. In this study, an ad-hoc parameterization was applied ignoring the facts that of each element roughness such as roads, houses etc.

3. Additional tests and improvement on the processing of LiDAR data. For example, for the processing of the last return data to be representative of actual elevation.

4. Land use and climate change scenarios calculations require the use of a rainfall runoff model output as an input to simulate boundary condition.

6.3. Recommendations for Department of Irrigation and Drainage Sarawak

For further improvement in the model, the followings are recommendations for the Department:

1. Based on this research, a need for accurate data and long term hydrological data series is identified. Existing hydrological data networks within Sg Sarawak catchments have to be maintained properly as incomplete and insufficient long term hydrological data sets have made modelling and trend analysis difficult. Therefore, establishing systematic hydrological data recording and monitoring schemes will facilitate the future modelling efforts.

2. It is recommended to develop and acquire relevant existing data and integrate those data into a spatially reference database to support decision making, planning scientific analysis and further modelling.
REFERENCES


