includes with model grid cells and extent, time step and length of simulation and type of output required and its frequency. The required parameters for calibration are bed resistance and wind friction factors. Hydrographic boundary conditions can be specified as a constant or variable (in time and space) level or flux at each open model boundary, as constant or variable source or sink anywhere within the model, and as initial free surface level map applied over the entire model.

The basic output of the 2-D Model is water surface elevation and flux densities in x-and y-directions. The derived output includes water particle velocity and flow direction, and the output results are computed at each grid point for each time step.

In very large basins, 1-D approach was a preferred choice for modelling floods; this is was due to significant requirements of topographic data and computational time for 2-D modelling. However, with advances in topographic data acquisition and processing techniques and advancement in parallel computing, 2-D modelling applications are increasing in river environment(Ahmad and Simonovic, 1999).

Among the several 2-D hydrodynamic models available today widely used models are:

2.5.2.1 RMA 2

RMA2 is a two-dimensional depth averaged finite element hydrodynamic numerical model developed by Norton, King and Orlob (1973)(GMS/WMS/SMS Group), It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields. RMA2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state (dynamic) problems can be analyzed using RMA2.

2.5.2.2 Delft-FLS.

Delft-FLS is specially suited to simulate the two dimensional dynamic behavior of overland flow over initially dry land, the influence of existing or future infrastructure on the flow pattern, as well as flooding and drying processes on every kind of geometry, in lowland and mountain areas. Delft-FLS is based on the finite differences method applied to a rectangular grid. It used very robust numerical scheme, known as the Delft or Stelling scheme which makes possible the simulation of both supercritical and subcritical flow, as well as flooding and drying without the use special procedures.

2.5.2.3 SOBEK-Urban

SOBEK-Urban is a comprehensive tool for a simple and complex urban drainage system. It consists of sewers and open channels. It can model the rainfall runoff process for various types of paved and unpaved areas. This model can also model street flow.
For hydrodynamic module, SOBEK-Urban used the complete Saint Venant equation including backwater and transient flow phenomena. Hydraulics structure can be specified virtually in the model to see its performance so that the urban drainage can be improved. The Real Time Control module allows the system to react optimally to water level, discharges and rainfall anywhere in the sewer system or its environment. The output can be superimpose over a GIS or Aerial Photo map of the area so sewer pipes, manholes, canals weirs and pumping stations can be seen at a glance. It also has animation option. This software is conforms to strict Dutch guideline for sewerage

calculation.
SOBEK-Urban consists of three modules:

- Hydrology
- Hydrodynamics
- Real Time Control

The SOBEK flow software is also a 1D-2D integrated model consisting with 1D and Delft FLS as 2D. It solves the Saint Venant flow equations and fully 2D shallow water equations in an implicit way using finite differences. It works for super and sub-critical flow and also it is capable to deal the wetting and drying areas.

2.5.2.4 RisUrSim(1D-2D).

The dual drainage model RisUrSim has been developed in order to meet the requirements of simulating urban flooding, focueing on the occurrence of distinct surface flow and its possible interaction with the surcharged sewer system(Theo G. Schmitta and Martin Thomasa and Norman Ettrich, 2004). It uses a 1D fully hydrodynamic model (dynamic sewer flow routing-HamokaRis) and a 2D model (RisoSurf) that solves the shallow water equations (Navier-Stokes equations) neglecting the inertia terms. Both models are coupled through the manholes and catch pits. The model was developed by ITWM (www.itwm.fhg.de).

2.5.2.5 MIKE 21.

MIKE 21 is a comprehensive modeling software for 2-D free surface flows, also developed by Danish Hydraulic Institute Water & Environment (DHI Group). It can be used for the simulation of hydraulic and related phenomena in rivers, lakes, estuaries, and coastal areas where stratification can be neglected. It can be used to simulate a wide range of hydraulic and related items, including tidal hydraulics, wind and wave generated currents, storm surges, dam break, water quality and flood waves. MIKE 21 is well suited for detailed analysis, design and management of flooding behaviour where a description of the 2D flow structure of rivers, lakes and their floodplains is required. This application have been tried to extend to urban areas where sometimes-2D flow description is required.

In MIKE 21, the hydrodynamic (HD) module is the basic computational module. The hydrodynamic module simulates water level variations and flows in response to a variety of forcing functions. The water levels and flows are resolved on a rectangular grid covering the area of interest when provided with the bathymetry, bed resistance coefficients, wind field and hydrographic boundary conditions. The software is capable to model the wide range of conditions likely to be encountered in urban areas like flooding and drainage of streets, parks, depressions, etc.

The modeling system solves the fully time-dependent non-linear equations of continuity and conservation of momentum. The solution is obtained using an Alternating Direction implicit (ADI) finite difference scheme of second - order accuracy. It simulates unsteady, two-dimensional flows in one layer (vertically homogeneous) fluids. MIKE 21 HD is based on the numerical finite difference solution of full nonlinear equations of conservation of mass and momentum integrated over the vertical to describe flow and water level variations. The application of the implicit finite difference scheme results in a tridiagonal system of equations for each grid line in the model. The solution is obtained by inverting the tridiagonal matrix using the Double Sweep algorithms, a fast and accurate form of Gauss elimination.

Data required for the development of a MIKE 21 model include:

Topographic data – Topographic data in x,y,z format to known horizontal and vertical references is required. The data should be collected at a resolution fine enough to describe urban features such as the buildings, streets, positions of divider and pavement and elevated roads. If the model is to simulate flooding in an urban environment, the location and footprint of buildings in the floodplain will also be required.

Boundary Data – Time series of flow or water level for the upstream and downstream boundaries of the area of interest. These data may be result of any suitable rainfall runoff model or constant discharge or otherwise depending on perception of flooding in the area or perhaps be extracted from a broader scale, one-dimensional model.

Roughness Coefficients – a value of roughness for the modelled area will be required. Roughness coefficients may be entered as a global value adopted for the whole model area, or a map of roughness coefficients varying for different streets reaches and floodplain areas may be developed and used. Variations of model roughness coefficient will form the basis of model testing regime in this study.

Structure Data – If the chosen model grid resolution is fine enough, hydraulic structures such as culverts and bridge piers may be represented with model grid elements. If a coarser grid size is used, the flow between grid points may be controlled by a stage/structure flow area curve similar to those commonly used in one-dimensional models. The equations for the conservation of mass and momentum integrated over the vertical to describe the flow and water level variations are as described in equations 4, 5 and 6 under section 2.5.2.

2.5.2.5.1 MIKE 21 model output

MIKE 21 HD provides output as time varying maps of water surface level and water flux in two dimensions (x-and y-directions) with scale values defined on the model grid specified by the user. MIKE 21 HD utilizes the MIKE Zero Graphical User Interface, which allows graphical interpretation of the model results. In addition data viewer in MIKE Zero can be used to view the data like velocities in both directions, speed, depth of flow and time series at a point in the model can be obtained..

2.5.2.6 MIKE FLOOD

MIKE FLOOD also developed by Danish Hydraulic Institute Water & Environment (DHI Group) is a tool that integrates the 1D-models MIKE 11/MIKE URBAN and the 2D-model MIKE 21 into a single, dynamically coupled modelling system. The coupled approach enables that best features of both 1D model and 2D model can be utilized, while at the same time avoiding many of the limitations of resolution and accuracy encountered when using MIKE 11, MIKE URBAN (MOUSE engine) or MIKE 21 separately.

Special features of MIKE FLOOD include:

- Momentum preservation through links,

- Lateral links, enabling simulation of over bank flow from river channel to flood plain,
- Comprehensive hydraulic structure package,
- Implicit structure links,
- Manhole links whereby the interaction of the sewer/storm system may interact with the overland flow,
- GIS integration,
- Links possible along any alignment in MIKE 21 (not just horizontally or vertically),
- A graphical user interface standard (MIKE ZERO), allowing easy data input and output as well as data preparation and analysis,
- A thorough on-line help system, user manual and technical reference documentation and
- Support and continuing commitment from DHI Water and Environment.

MIKEFLOOD has many advantages and many model applications can be improved through its use, including: Floodplain applications, storm surge studies, urban drainage, dam break, hydraulic design of structures and broad scale estuarine applications.

By combining the three systems available under MIKE FLOOD (MIKE 11, MIKE URBAN and MIKE 21), the modeler can choose the best features of each and make the best model with these features. MIKE FLOOD enables this integration to be performed easily, but it is still the modeler who decides how to design the integrated model.

2.5.2.6.1 General description of MIKE FLOOD

There are five different types of linkage available within MIKE FLOOD. Four of these link MIKE 11 and MIKE 21whereas the last one is reserved for linking a node/manhole in MIKE URBAN with one or more cells/elements in MIKE 21.

2.5.2.6.1.1 Standard Link

This is the standard linkage in MIKE FLOOD, where one or more MIKE 21 cells are linked to the end of a MIKE 11 branch. This type of link is useful for connecting a detailed MIKE 21 grid into a broader MIKE 11 network, or to connect an internal structure (with an extent of more than a grid cell) or feature inside a MIKE 21 grid. The Potential applications are shown on Figure 7.

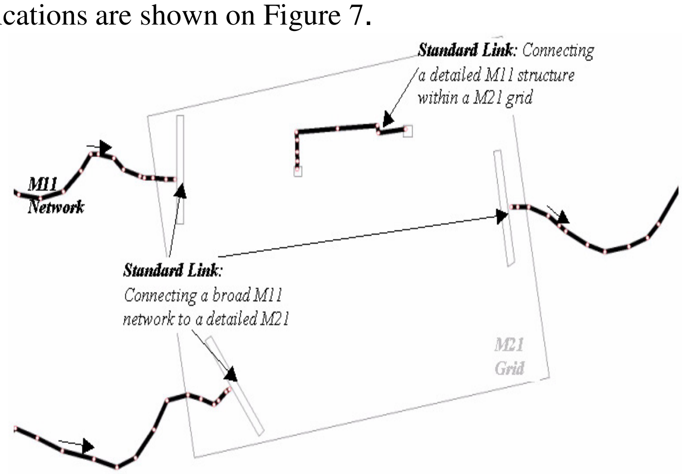

Figure 7: Application of Standard Links

2.5.2.6.1.2 Lateral Link

A lateral link allows a string of MIKE 21 cells to be laterally linked to a given reach in MIKE 11, either a section of a branch or an entire branch. Flow through the lateral link is calculated using a structure equation or a QH table. This type of link is particularly useful for simulating overflow from a river channel onto a flood plain, where flow over the river levee is calculated using a weir equation. An example is shown on Figure 8.

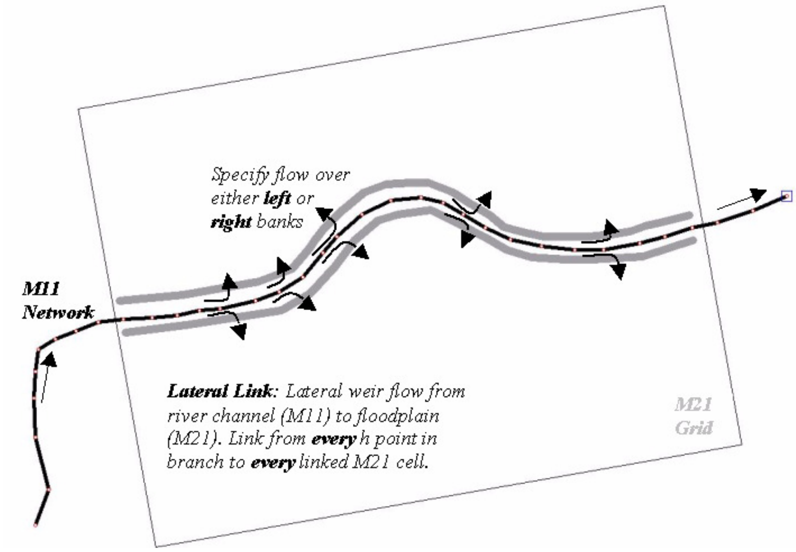

Figure 8: Application of Lateral Links

2.5.2.6.1.3 Structural Link

The structure link takes the flow terms from a structure in MIKE 11 and inserts them directly into the momentum equations of MIKE 21. This is fully implicit, so should not affect time step considerations in MIKE 21.
The structure link is useful for simulating structures within a MIKE 21 model. The link consists of a 3 point MIKE 11 branch (upstream cross- section, structure, downstream cross-section), the flow terms of which are applied to a MIKE 21 cell or group of cells. An example is shown on Figure 9.

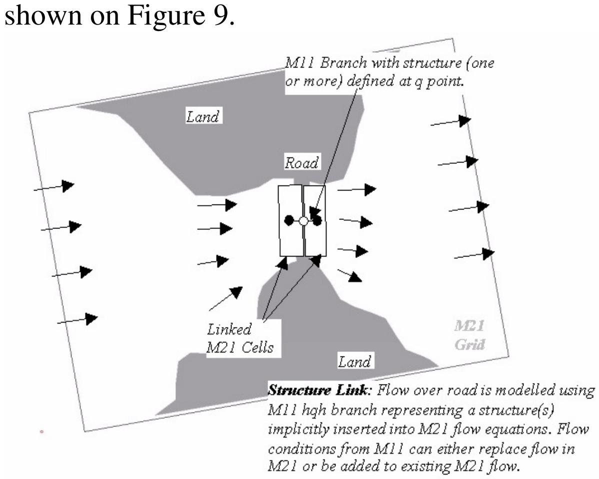

Figure 9: Application of Structural Links

2.5.2.6.1.4 Urban Link

The urban link is designed to describe the interaction of water when the manhole is over topped (Figure 10) or when overland flow enters the sewer/storm water network (Figure11).

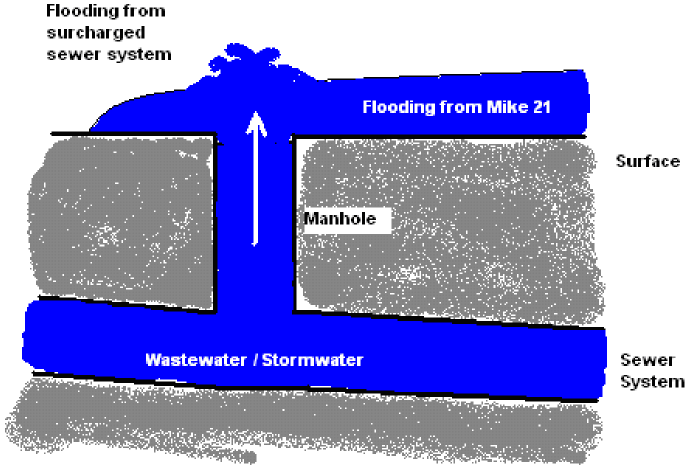

Figure 10: Flooding from a surcharged sewer system into MIKE 21

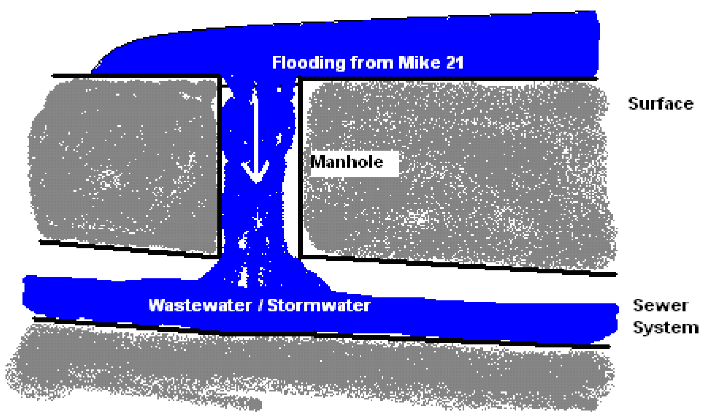

Figure 11: Flooding from MIKE 21 into a non-surcharged sewer system

The link is designed such that one or more cells in MIKE 21 may be linked to a manhole/node in MOUSE/MIKE URBAN.

2.5.2.6.1.5 Zero Flow Link (X and Y)

A MIKE 21 cell specified as a zero flow link in the x direction will have zero flow passing across the right side of the cell. Similarly, a zero flow link in the y direction will have zero flow passing across the top of the cell. The zero flow links were developed to complement the lateral flow links. To ensure that floodplain flow in MIKE 21 does not travel directly across a river to the opposite side of the floodplain without passing through MIKE 11, zero flow links are inserted to block MIKE 21 flows. An alter-native to using the zero flow links is to apply land cells which, depending upon grid resolution may not be appropriate.

Another useful application of zero flow links is to represent narrow block- ages on a flood plain, such as roads and levees. Rather than using a string of land cells, a string of zero flow cells can be used. It will be noted that, this link is only available when linking to MIKE 11.

2.6 Model Selection

Due to hydrological and hydraulic uncertainties in flood modelling, estimation of the extent of floodplain inundation has been, and will continue to be a challenging issue. In order to identify areas subjected to flooding, urban flood modeling techniques are proven to be useful. These models provide the basis on flood management and control and further as means for solving engineering problems.

The choice of a suitable model for flood simulation depends on the purpose of the overall project and the problem to be solved. For example, in river flood modeling, if a building is being built on the flood plain such that the building will not significantly affect the flooding characteristics of the river, but it will be sensitive to flooding, the authority may be concerned with the peak water level at the construction site and also in how long the flood will be above a certain level, here the shape of the stage hydrograph will be interested (Kazi Emran Bashar, 2005). Also the quality and amount of data including with geometry of the channel and floodplain, terrain models (DTM and DEM), magnitude and variation of the width of the floodplain along the channel are important factors to be considered in the choice of a simulation model.

In this research, the coupled 1D-2D modeling approach was used. The modeling software used consists of MIKE 11 model as 1D free surface flow model for stormwater channel modelling and MIKE 21 as 2D free surface flow model for floodplain modelling and MIKE FLOD for coupling MIKE 11 and MIKE 21 models.

3 METHODOLOGY

3.1 Approach

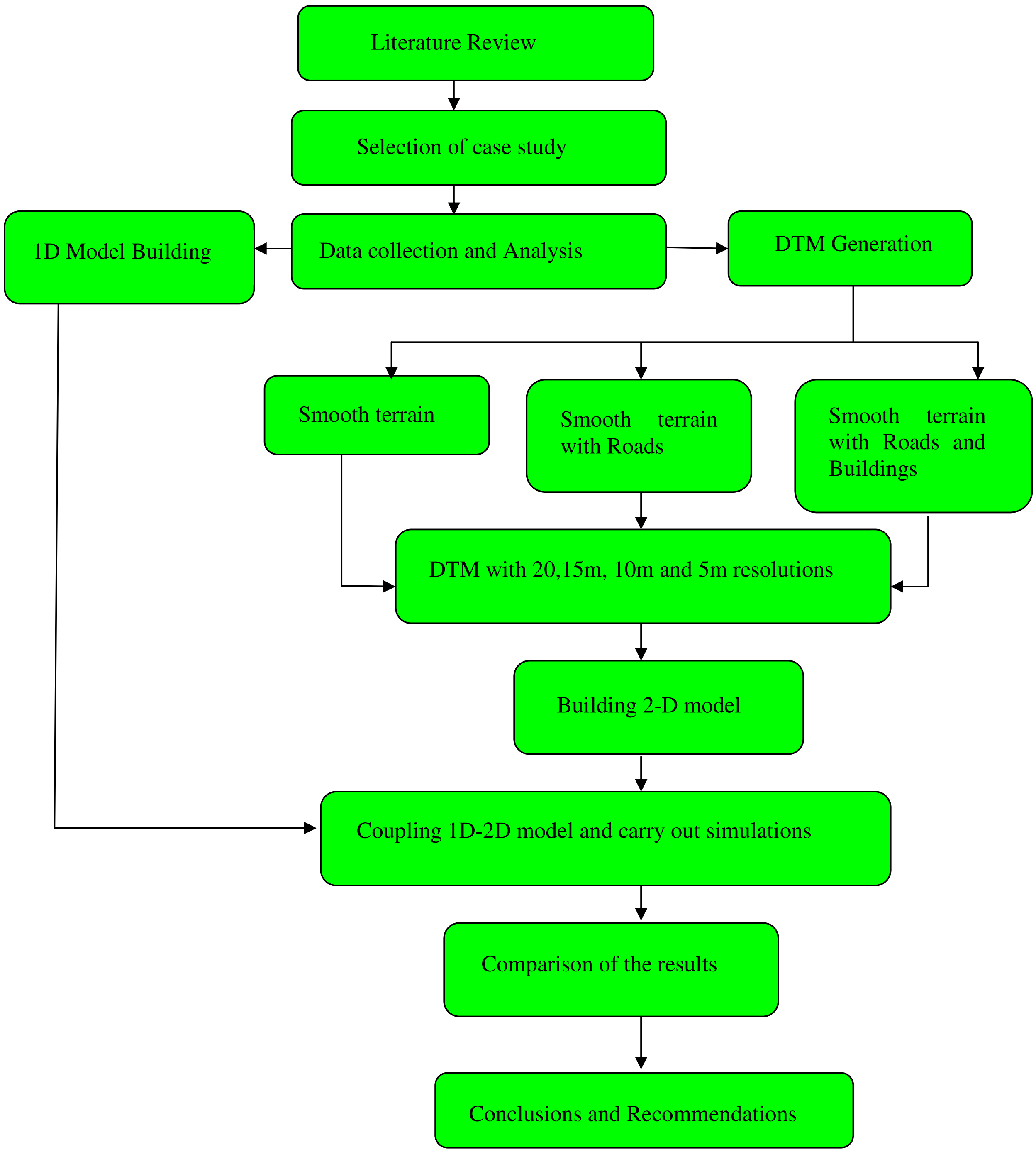

Figure 12: The flow chart of methodology applied in this Research

3.1.1 Selection of Case Study area.

Based on data availability, the study area of this research was chosen to be from St.Maarten N.A. The Cul De Sac catchment area (Figure 13) was used to carry out the research work. Details of the study area refer to section 3.3

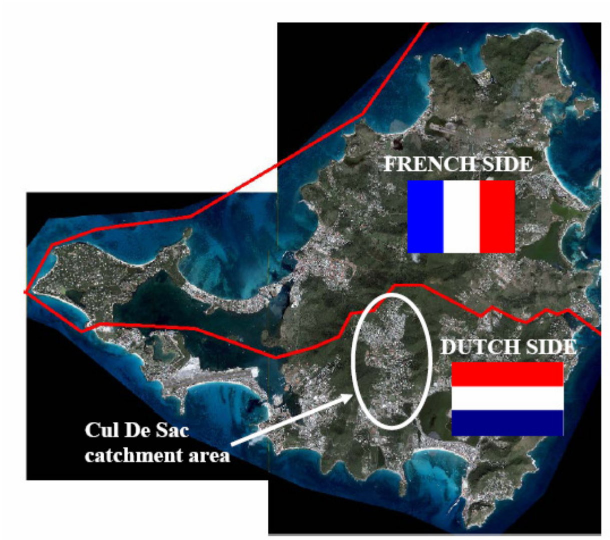

Figure 13: The Cul De Sac catchment area
(Adopted from (Tutulic', 2007))

3.1.2 Data Collection and Analysis

Fieldwork is very important for every project for the purpose of collecting essential data for the study. This helps to understanding the existing conditions and to collect the considerable data for model. Those data is based on the selected tools to be used in the study and expected output. In this study, the data available from UNESCO-IHE is St. Maarten project included: contour maps/terrain data, road network shape file map, building shape file map, stormwater channel network, rainfall (rainfall event with intensity of 150mm/hour) was used.

3.1.3 1D model Building

Building of 1D model was done using the existing cross sectional and chainage data (Tutulic', 2007) using MIKE 11 modelling systems. The computational points from existing MIKE11 network was opened into Microsoft Office excel and saved as DBF IV format (*.dbf). These points were then added into ArcGIS and by right hand click the, the X, Y data was specified. To get the elevation of the computational points based on the prepared Digital Terrain Models with resolutions 5m, 10m,15m and 20m, the existing computational network points was extracted using ArcGIS toolbox/ Spatial Analyst tools/Extraction/ Extract the values to the points. All other parameters such as boundary data (hydrographs), rainfall runoff parameters and hydrodynamic parameters were used as from the previous study. Only the cross sections were changed to V-shapes for research purposes. The same depth of the network was used for all Digital Terrain models in order to retain the same capacity of the channel network.

3.1.4 Terrain model Building

A Digital terrain model (DTM) is a crucial starting point for building a 2D hydrodynamic model. The technology such as Airborne Laser Scanning (ALS) or Light Detection and ranging (RIDAR) is used in providing a comprehensive topographic coverage of entire floodplain areas in an accurate and economic manner. In order to provide a good spatial framework a sufficiently fine resolution of the data is required to compensate for a course resolution of the hydrodynamic model (Tutulic', 2007). In this study, the following 12 DTMs were developed:

- DTM with resolutions (grid scale of 5m, 10m, 15m and 20m) for smooth land surface with hydraulic roughness coefficients (Manning's number 20 and 30).
- DTM with resolutions (grid scale of 5m, 10m, 15m and 20m) for land surface with road network with hydraulic roughness coefficients (Manning's number 20 and 30).
- DTM with different resolutions (grid scale of 5m, 10m, 15m and 20m) for land surface with road network and buildings with hydraulic roughness coefficients (Manning's number 20 and 30).

Table 2: Summary of models developed in this study

Model	Geometry	Resolution	Manning's Number
5	Smooth land surface only	5m x 5m	20
			30
10	Smooth land surface only	10 x 10m	20
			30
15	Smooth land surface only	15m x 15m	20
			30
20	Smooth land surface only	20m x 20m	20
			30
5a	Land surface with Road network	5m x 5m	20
			30
10a	Land surface with Road network	10m x 10m	20
			30
15a	Land surface with Road network	15m x 15m	20
			30
20a	Land surface with Road network	20m x 20m	20
			30
5b	Land surface with Road + buildings	5m x 5m	20
			30
10b	Land surface with Road + buildings	10m x 10m	20
			30
15b	Land surface with Road + buildings	15m x 15m	20
			30
20b	Land surface with Road + buildings	20m x 20m	20
			30

3.1.5 Building 2D model

This was done by preparing the bathymetry using ascii file prepared in ArcMap. The ascii files was prepared by converting the Digital Terrain models prepared under 3.1.4 into ascii file using conversion tools found in ArcGIS. Different bathymetry with digital terrain model resolutions of 5m, 10m, 15m and 20m was prepared in different geometries, i.e., land with smooth surface only, land with smooth surface plus roads and land with smooth surface, roads and buildings. After getting the bathymetry, the MIKE 21 flow model was then prepared keeping all basic parameters and hydrodynamic parameters as in the previous studies except the roughness coefficient in hydrodynamic parameters. Based on research objectives, two values of roughness coefficient (Manning's number) of 20 and 30 were used in the model.

3.1.6 Building the coupled 1D-2D Model

After building the 1D and 2D models using MIKE11 and MIKE21 software respectively, the coupled 1D-2D model was then prepared in MIKE FLOOD software. This was done by linking a 1D open channel drainage network (MIKE11) and 2D surface (MIKE21). The lateral link option was used for coupling MIKE11 and MIKE21

3.1.7 Carrying out simulations

After building the coupled MIKE FLOOD, the simulation for Digital Terrain Models was carried out using a rainfall event of 150mm/hour intensity. In terms of the 2D model parameters the roughness coefficient (Manning's number) of 20 and 30 was used.

3.1.8 Simulation result analysis

The model simulation outputs including the peak discharge, water level and velocity maps were analysed and compared between different scenarios.

3.1.9 Conclusions and recommendations

Further to the analysis of the results, conclusion and recommendations were drawn and outlined at the end of this thesis.

3.2 Tools used.

In order to carryout the research and to meet the intended objective, the following tools were used: Arcmap, MIKE11, MIKE21, MIKEFLOOD and waterRIDE.

3.2.1 ArcMap

ArcMap is the ArcGIS tool used to create and visualize various types of geographic data, including maps and map features (West Virginia GLOBE. West Virginia View). ArcMap is the application used to view and edit geographic data, query spatial data to find and understand relationships among geographic features, and create professional quality maps, graphs, and reports. It allows users to create and interact with maps. A map is the fundamental component to work with in ArcMap. Maps help to visualize geographic data by showing where things are and what they look like(Michelle Zeiders, 2002). ArcMap is the product of ESRI and it represents the most application for desktop geographic information systems (GIS) and mapping. ArcMap is also used to resolve basic geographic questions of location, size, juxtaposition, and can even answer "WHAT IF?" "How much...?" and "Where is...?" questions - geographic modeling scenarios.

3.2.2 waterRIDE Software Package

waterRIDE is an acronym for Water Resources Integrated Development Environment. The software was developed by Patterson Britton & Partners Pty Ltd Company from Sydney, Australia. It is a suite of software components for creating tools to serve GIS functionality and connectivity to traditional water resource applications.

The GIS functionality includes a basic engine for displaying, zooming, panning map layers and extracting spatial data from them. The connectivity provides a means of integrating water resource datasets, such as flood modelling results with GIS layers, where the water resource datasets are mapped to a spatial framework and can include time varying data suitable for animation. In this manner, complex water resource investigation results can be visualized in a controlled graphical display, and integrated and connected to geographical information system data such as cadastre. Information from the water resources domain can be converted back to the GIS data files for further analysis and distribution with corporate GIS tools.

Two dimensional flood modelling packages typically generate complex and extensive data results that require a degree of interpretation before a wider distribution of planning and end implementation. waterRIDE provides the user with a rich suite of tools to creatively display and investigate typical results for a variety of different possible scenarios. Once meaningful displays have been appropriately interpreted and created, they can be distributed to the end user (communities) in a package that facilitates ease of use and access, whilst protecting the data and inappropriate access to the sensitive information.

Three main types of files can be displayed in the main viewing window of the waterRIDE interface. These are:

• Georeferenced images - file types such as bitmaps (*.bmp files), JPEGs (*.jpg and *.jpeg files), and Enhanced Compressed Wavelet (*.ecw files), MrSID files (*.sid), and JPEG2000 files (*.jp2, j2k) with defined bottom-left coordinates and pixel size,

• GIS files - files from GIS packages such as ArcGIS (*.shp files) and MapInfo (*.mif/mid files) and

• Result data files - Depending on the specific waterRIDE application, various hydraulic model results can be displayed (such as: RMA, MIKE 21, MIKE 21, TUFLOW, SOBEK, DRAINS, ESTRY, HEC-RAS etc.). waterRIDE can read and display model output results in a specific file format. These files may be read natively or translated into the waterRIDE binary format (*.wrb). A description of the structure and format of .wrb files is provided in a separate document.

In addition to these spatially referenced data files, non-spatially referenced data including text (*.txt and *.rtf files), tables (*.csv files), photographs (*.bmp and *.jpg files), multimedia (*.avi and *.mpeg files), Microsoft Excel spreadsheets, (in fact, any OLE compatible file - a file that can be opened by "double clicking" in windows explorer) from external sources can be linked to objects in GIS files displayed by waterRIDE. These files can be displayed in a separate Links Display Window when certain objects in a GIS layer are selected with the mouse.

3.3 Description of the Case study

The research work was carried out using the data from St. Marten, N.A. St. Maarten is one of the five islands that form the Netherlands Antilles, which in turn is a part of the Kingdom of the Netherlands. This Kingdom comprises of the Netherlands, Dutch Antilles, and Aruba. This unique island is located approximately 280 miles east of Puerto Rico, or 18.1 degrees north and 63.3 degrees west. St. Maarten is unique in that it shares the island with St Martin, a French dependency that occupies 21 square miles on the northern part of the island. The area comprises the Dutch side of the Island Territory having area of approximately 3380ha. The north and south side of the area is bonded by the French side of the island and the Caribbean Sea respectively (figure 14). For the past of 10 years St. Maarten has characterized with increase in both residential and commercial infrastructure that further led in increasing the covered surface areas which result in reduction of the rainfall infiltration into the ground.

Large areas of the island are steep with irregular geometry (figure 15) with elevation of the area, ranging from near sea level at the southern end to 380 m above mean sea level at the northern hilly part along the borderline. Overland flows converge towards the low-lying areas and the stormwater runoff is discharged at many locations. This is due to improper design of the channel. The drainage network in the area is mainly lined and natural channels, natural waterways and roads.

Figure 14: Location of St. Maarten Island.
(**Source:** **http://www.worldatlas.com**)

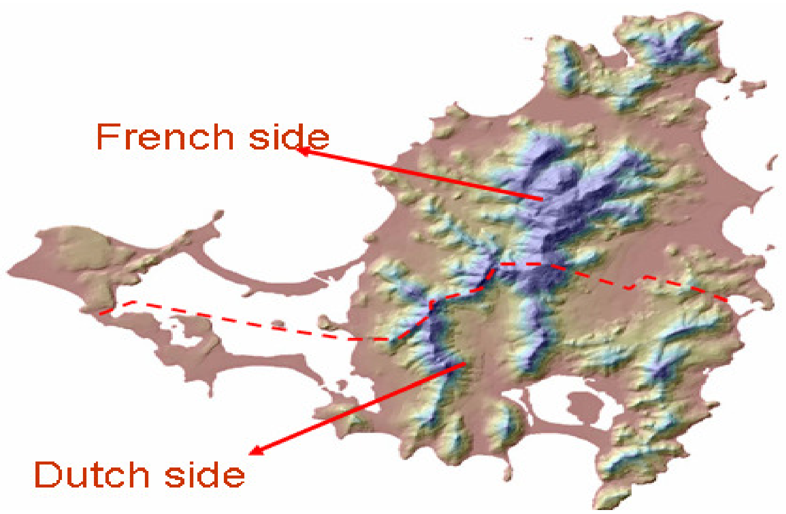

Figure 15: Topography of St. Maarten Island
(Adopted from Vojinovic, 2006)

The main Cul De Sac area, being surrounded by the mountains and relatively close to the sea shore, is subjected to orographic rainfall. It is a type of precipitation which occurs when an air-stream crosses a mountain barrier.

The Climate of St.Maarten is characterized by wet season over several months, heavy rainfalls exceeding 150mm/hr intensities and a higher mean temperature throughout the year; this is due to the area being in tropical climate. Urban environments on St. Maarten are situated on low-lying areas, with little consideration for stormwater drainage and as such they are subject to flash flooding from surrounding hills, or extreme rainfall events such as direct thunderstorms. The area is also characterized with short stormwater channels and they are inadequate to convey excess rainfall-runoff due to limited capacity, obstructions and morphological rising of the streambed.

Due to inadequate development control, the streets in residential area are almost as such the limiting factor for enlargement of storm water channels (Figures 16). The island of St.Maarten is frequently affected by flash flood (figure 17) caused by intensity of the subtropical rainfalls and mountainous morphology. The flooding in the area has becoming a serious problems not only in severe property and infrastructure damages but also with increasing incidence of injury and in the recent two people lost their lives (31st July 2005). The topography of the area is predominantly steep with irregular geometry.

Figure 16: One of the residential streets after the storm.

Figure 17: Flash flood occurred in 30th July 2005.

Most of the studies in the island of St. Maarten for urban flood modelling and flood management, so far, have been done using either 1D, 2D or coupled 1D-2D models. In order to describe the flood waves across the flood plains in the area (Tutulic', 2007) applied the flood plain modelling with 1D and 2D models. (Tutulic', 2007) has made an attempt to use a coupling of 1D-2D modelling approach whereby one dimensional open channel flow model was combined with two-dimensional model of flood plain and to compare the result with 1D model. The findings show that for steep terrain and highly urbanised area, a 1D-2D modelling approach can be sufficient to represent physics of the phenomena. In terms of the flat terrain (terrain topographies with no changes in elevation), the result obtained from 1D model and 1D-2D modelling approach do not show significant difference. One of the shortcomings of the previous study was that effects of model schematization with different DTM resolutions and different land use have not been assessed.

Therefore the present study covers mainly issues associated with schematisation, geometry and parameter values and their affects on simulation results. The DTM representation of the St.Maarten N.A case study is shown in figures 18

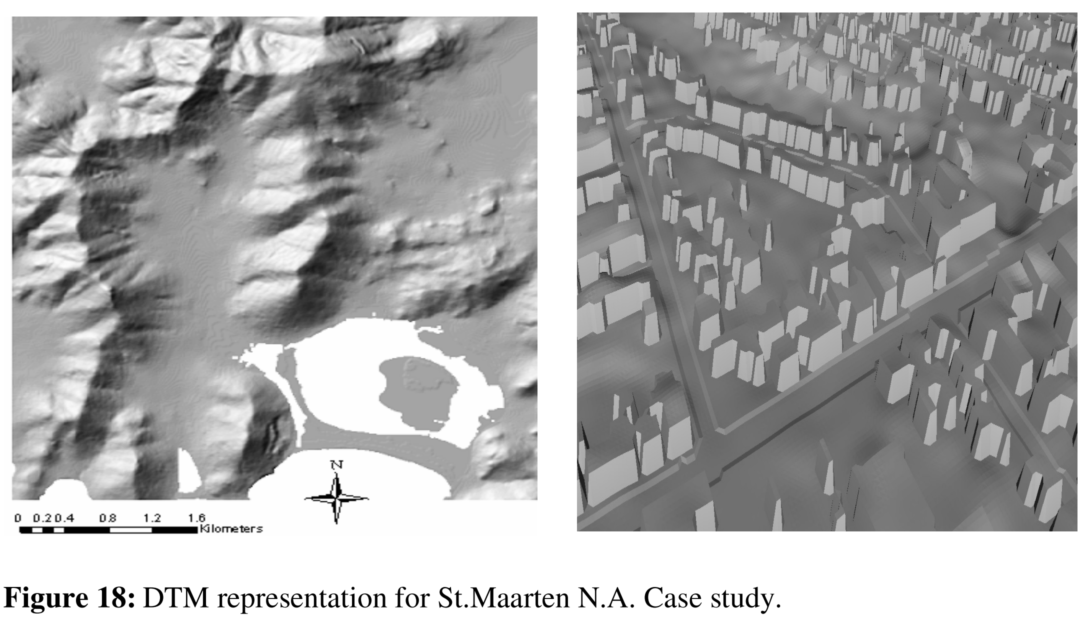

Figure 18: DTM representation for St.Maarten N.A. Case study.
Left: Land Surface only, Right: Land Surface, Roads and Buildings (Adopted from Vojinovic and Tutulic, 2007)

4 DTM GENERATION

4.1 Introduction

In the case of urban flood modelling with the use of a 2D surface model, the topography has to be very accurate represented to permit reproducing the natural flows as good as possible. When the flood affects any floodplain, an accurate topographic representation of the floodplain is needed, which is always provided in the form of Digital Terrain Model (DTM). One of the main problems is frequent land use changes in major cities, where frequent updating of the DTM for flood modelling might be needed. A DTM that includes surface features such as buildings is customarily referred to as Digital Elevation Model (DEM). Most widely used DTMs and DEMs for flood modelling applications are made of a collection of surface elevation values on a regular square grid (Sylvain NÉELZ and PENDER, 2007).

In urban area, features like roads, buildings, river banks and dykes have great effects on flow dynamics and flood propagation, and as such must be accounted for in the model set up. Overland flows are primarily conveys along the roads. Buildings and other structures changes the direction of flow. Accountability of urban features is possible by means of high resolution input data that relates to the systems topography as well as to the identified features. Society demands accurate and detailed information on magnitude and likeliness of hazardous flood events for design flood mitigation measures. Therefore in 2D modelling, accurate representation of buildings and roads within the Digital Terrain Model (DTM) is crucial. In this research, DTMs with natural (Smooth) surface, Smooth with Roads and Smooth with Roads and buildings was generated using ArcGIS Software for comparison purposes.

4.2 Data used for DTM generation

In this study the following shape files data was used to generate the DTM for the St. Maarten N.A case study.

- Contour lines map
- Road network map
- Building structures map
- Extent of the study area
- Ponds map

The above listed data has been previously generated for entire Island. However, using the Clip tool for shape file located under Analysis Tools/Extract, the DTM was adjusted to the size of the coverage area required for the study. The DTM was created first as a smooth (natural) land surface without including buildings and road network in 20x20m, 15x15m, 10x10m and 5x 5m cell sizes followed by lowering road elevation for 25cm and raising building elevations for 5m.

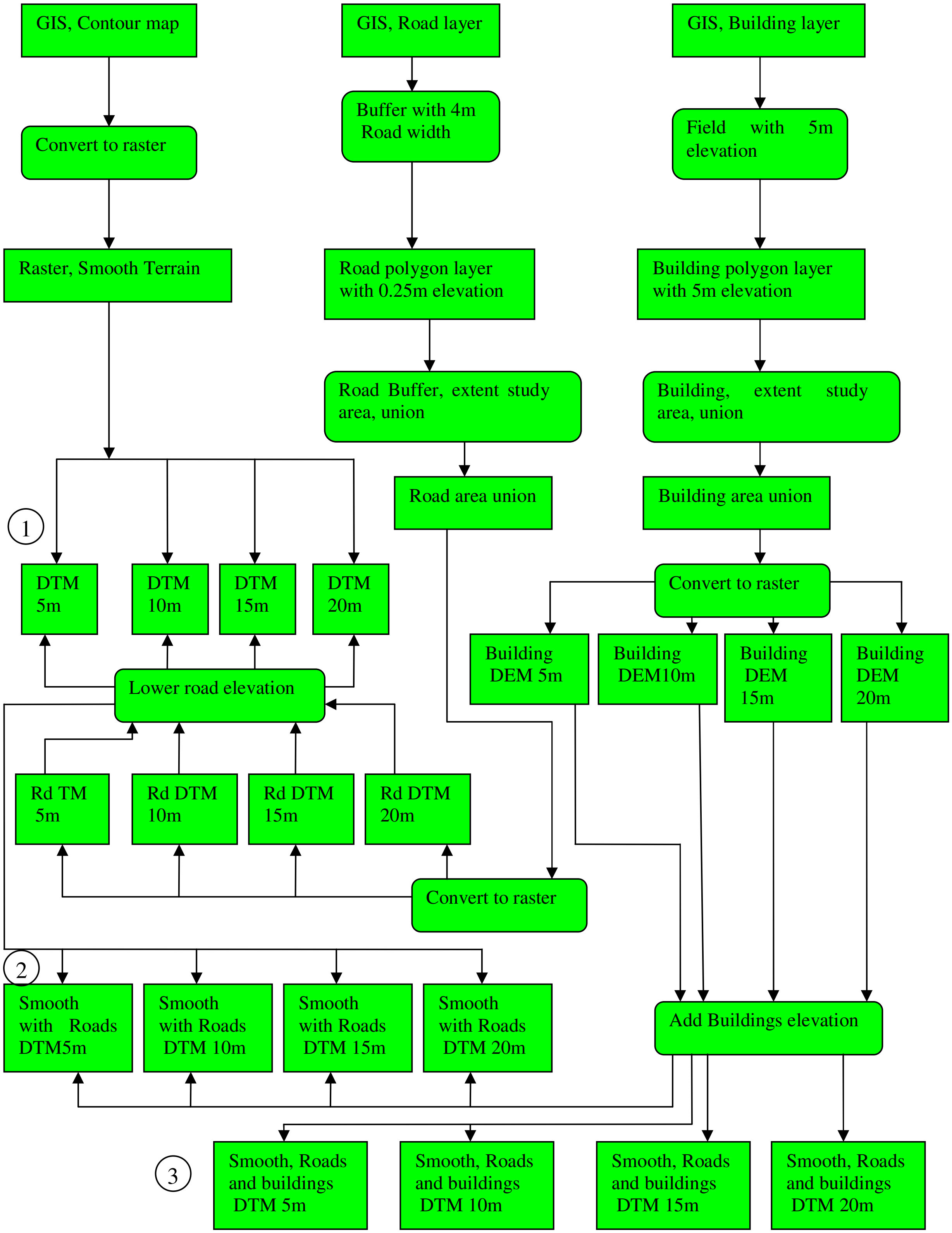

Figure 19: Flow chart for DTM generation

4.3 DTM of natural (Smooth) surface

Based on the objective of the study, separate DTMs for natural surface, road surface and buildings were developed with different grid cells and then used as input for 2D hydrodynamic model.

The DTM was created based on Topo to Raster interpolation tool available in ArcGIS with Spatial Analyst Extension and contour map as input shape file. The Topo to Raster function is an interpolation method specifically designed for the creation of hydrologically correct Digital Terrain Model (DTM)(ESRI, 2006). It interpolates elevation values for a raster, imposing constraints that ensure a connected drainage structure and Correct representation of ridges and streams from input contour data. Topo to Raster is the only ArcGIS interpolator specifically designed to work intelligently with contour inputs. It is uses information inherent to the contours to build a generalized drainage model. By identifying areas of local maximum curvature in each contour, the areas of steepest slope are identified, and a network of streams and ridges is created (Hutchinson, 1988). This information is used to ensure proper hydrogeomorphic properties of the output DTM and may also be used to verify accuracy of the output DTM.

In this study, DTM has been generated based on shape files data including with contour maps/terrain data obtained from the previous study. All these data has previously generated as a whole Island. Using the Clip tool for shape file located under Analysis Tools/Extract, the DTM was adjusted to the size of the coverage area required for the study. The contour map and study area shape file was used as input features and clip features respectively. The DTM with 20 x 20m, 15 x 15m, 10 x 10m and 5 x 5m resolutions was created first as a smooth land surface without including buildings and road network by specifying a value of 20, 15, 10 and 5 as output cell size respectively (see figures 20, 21, 22 and 23).

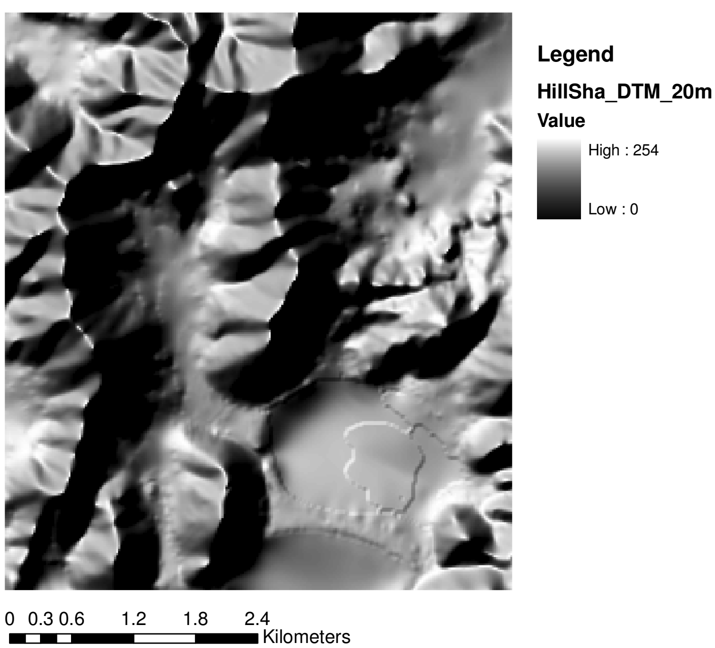

Figure 20: DTM with Smooth Land Surface- 20m Resolution

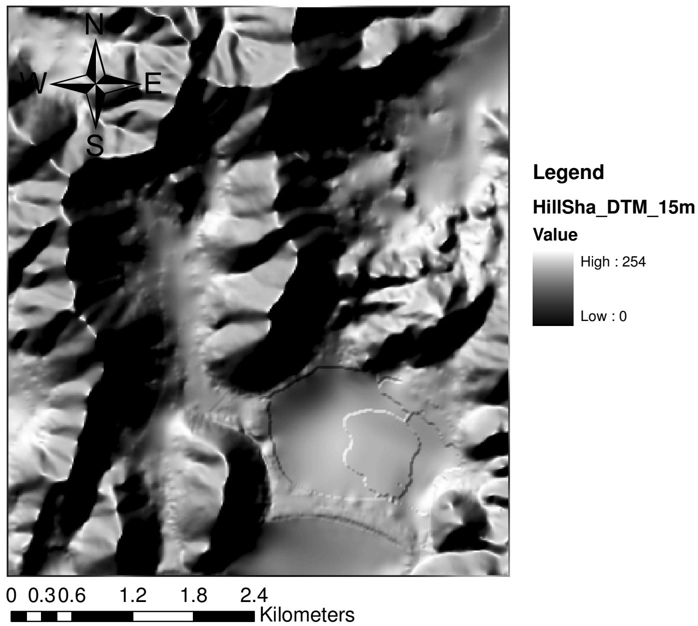

Figure 21: DTM with Smooth Land Surface- 15m Resolution

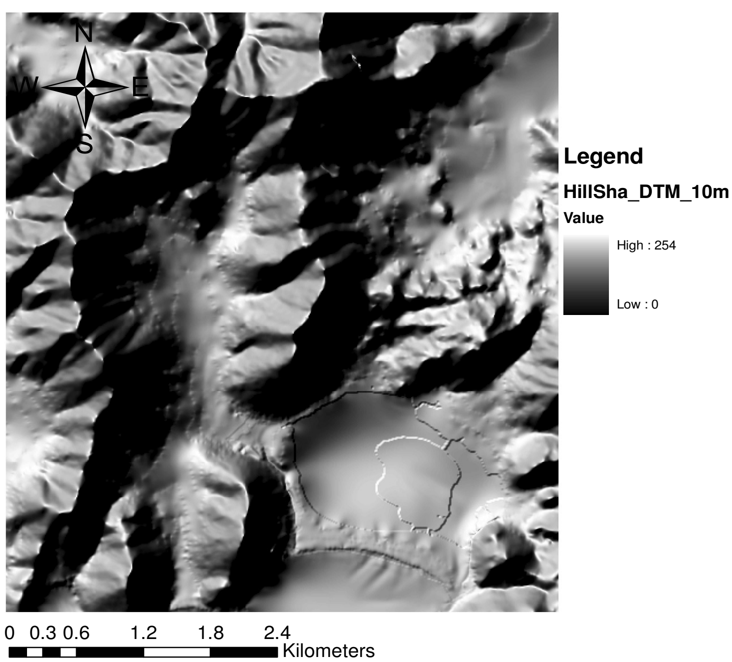

Figure 22: DTM with Smooth Land Surface- 10m Resolution

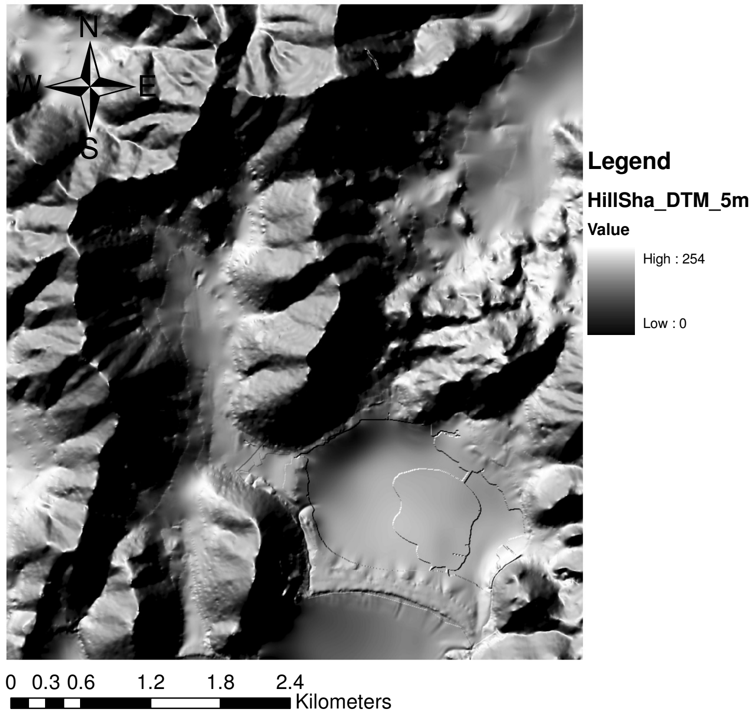

Figure 23: DTM with Smooth Land Surface- 5m Resolution

4.4 Adding terrain information in the DTM with Smooth Surface

For accurate analysis of urban flooding, it is necessary to incorporate terrain features like buildings and road networks in DTM. In this research, road network and buildings were incorporated using ArcMap GIS tools with smooth land surface DTM obtained from section 4.3. For the features to be seen on the figure, the feature Hillshade found on spatial analyst tools/Surface/Hillshade was used.

4.4.1 Adding road network in the DTM

Addition of road network to the DTM with smooth land surface has been carried out using ArcGIS with analysis tools. This has been done by lowering the road level by the curb height. Due to lack of detailed information, an average curb height of 25cm has been used for the main streets of the model area with width of 4m.

In ArcGIS, the polyline road network shape file was first converted to a polygon shape file with 4m width using Analysis Tools/proximity/buffer. The field where the elevation of 25cm modification induced by the road to be in stored, has then added to the polygon file. For a better mathematical operation between the topography raster and a road raster, the study area extent shape file has been added to a road network shape file by making a union between the polygon road shape file and a study area shape file using Analysis Tools/Overlay/Union. The road area DTM was then created by converting the union shape file to a raster file using ArcToolbox/ Conversion Tools/ To raster/Feature to raster. Different DTM with 20x20m, 15 x 15m, 10 x 10m and 5 x 5m was created by specifying a value of 20, 15, 10 and 5 as output cell size respectively.

The final DTM with smooth and road network was created by lowering the topography at the place where there are roads using mathematical operation found on ArcToolbox/ Spatial analyst tools/Maths/Minus. In this operation, the DTM with smooth land surface and road area was used as input raster file. The final DTM with road networks are as shown in figures 24, 25, 26 and 27.

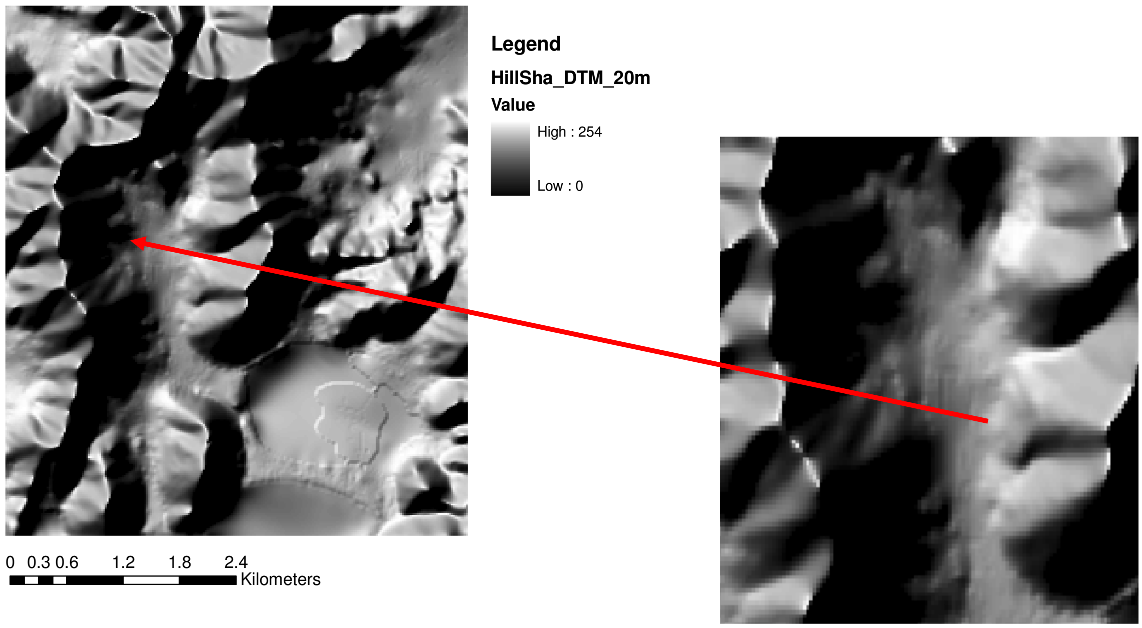

Figure 24: DTM with Smooth and Road network- 20m Resolution

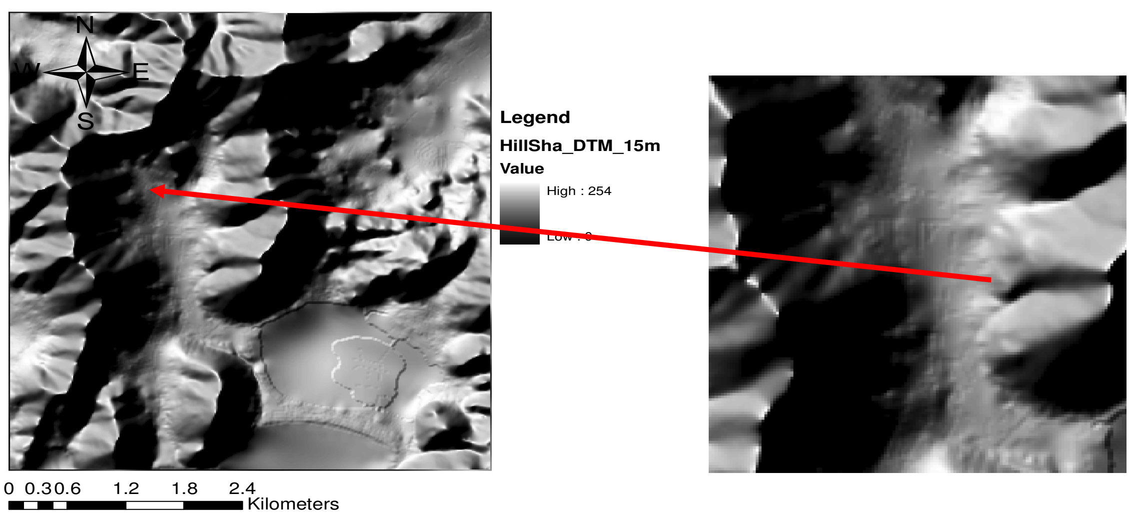

Figure 25: DTM with Smooth and Road network- 15m Resolution

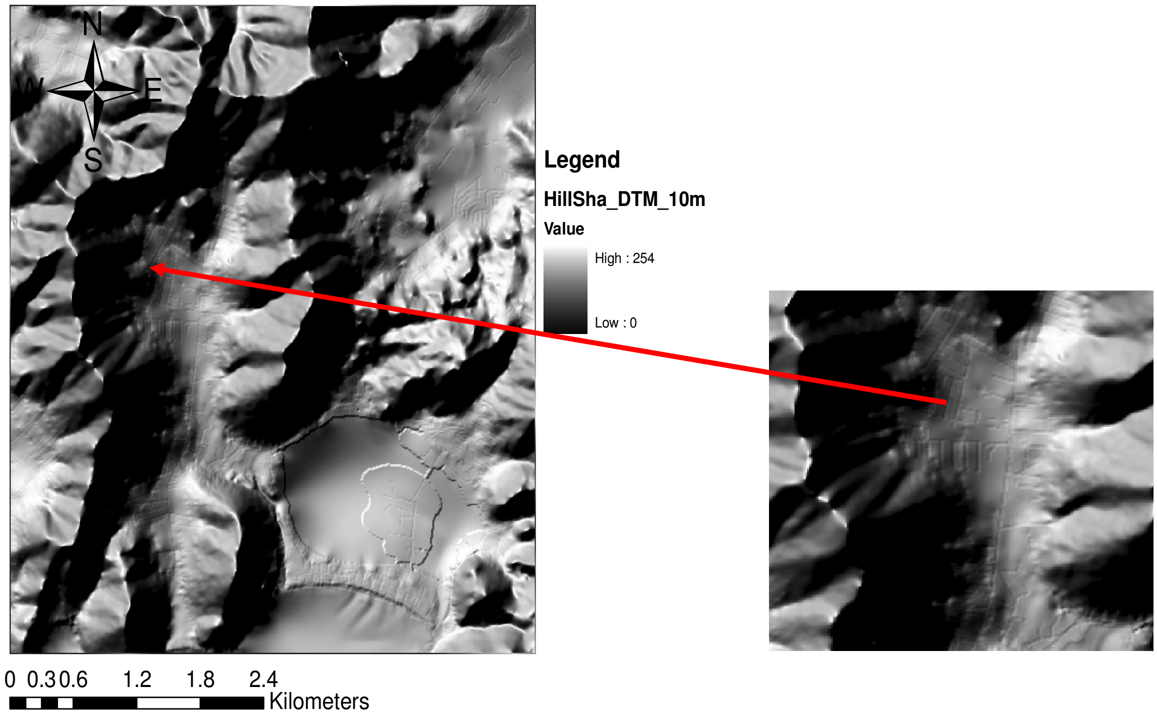

Figure 26: DTM with Smooth and Road network- 10m Resolution

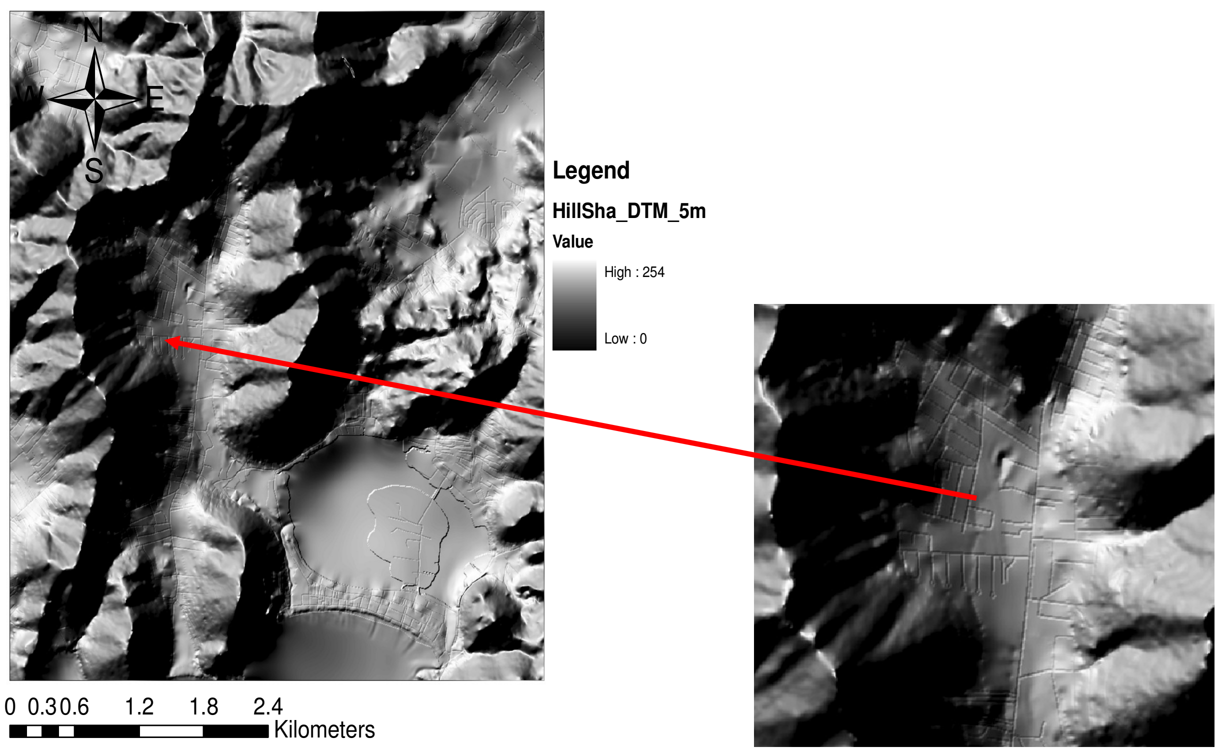

Figure 27: DTM with Smooth and Road network- 5m Resolution

4.4.2 Adding Buildings and Road network in the DTM

In a densely developed urban area, during flood event the direction of overland flow are primarily governed by buildings and structures present in the terrain. Therefore accurate representation of buildings footprints in DTM as an obstruction to the flow is essential in hydrodynamic modelling.

The DTM with Buildings and Road network was created by adding building block to the DTM with road network prepared under section 4.4.1 above. This was done by raising the building block by an average value of 5m. The arbitrary height was used to convert building footprint feature class into a raster layer representing a building height, as a pixel value.

In ArcGIS, the field with an average elevation of 5m was added to the building shape file, and the study area shape file was added to a building shape file using Analysis Tools/Overlay/Union. The building area DTM was created by converting the union shape file to a raster file using ArcToolbox/ Conversion Tools/ To raster/Feature to raster. Different DTM with 20x20m, 15 x 15m, 10 x 10m and 5 x 5m was created by specifying a value of 20, 15, 10 ad 5 as output cell size respectively.

The final DTM with building and road network was created by raising the buildings with average elevation of 5m using mathematical operation found on ArcToolbox/ Spatial analyst tools/Maths/plus. In this operation, the final DTM with road network and building area DTM was used as input raster file. The final DTM with buildings and road networks are as shown in figures 28, 29, 30 and 31.

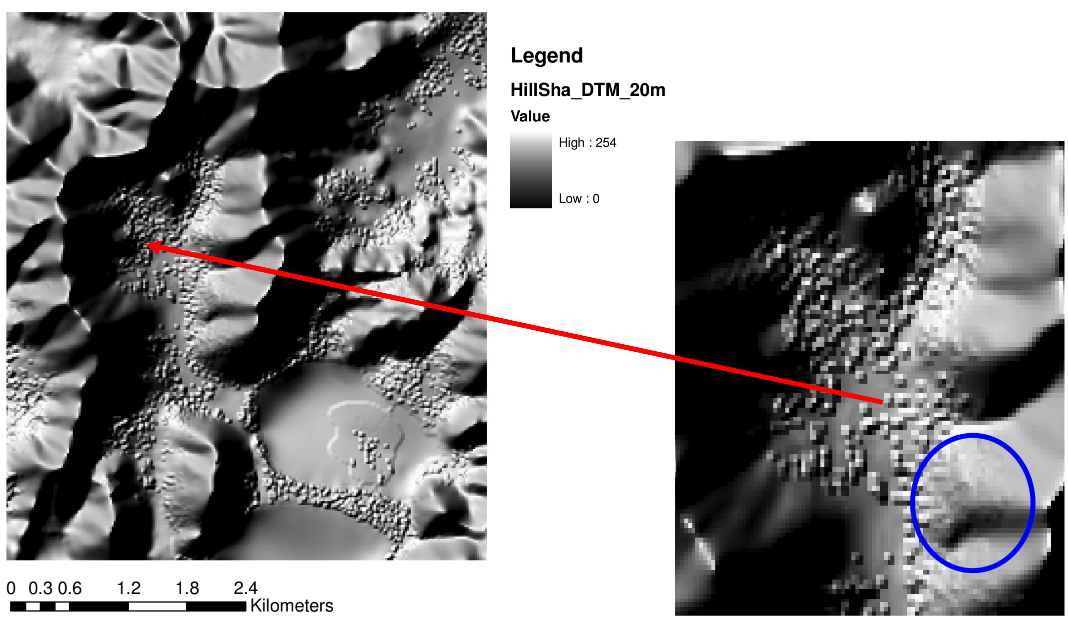

Figure 28: DTM with Smooth, Road network and Buildings- 20m Resolution

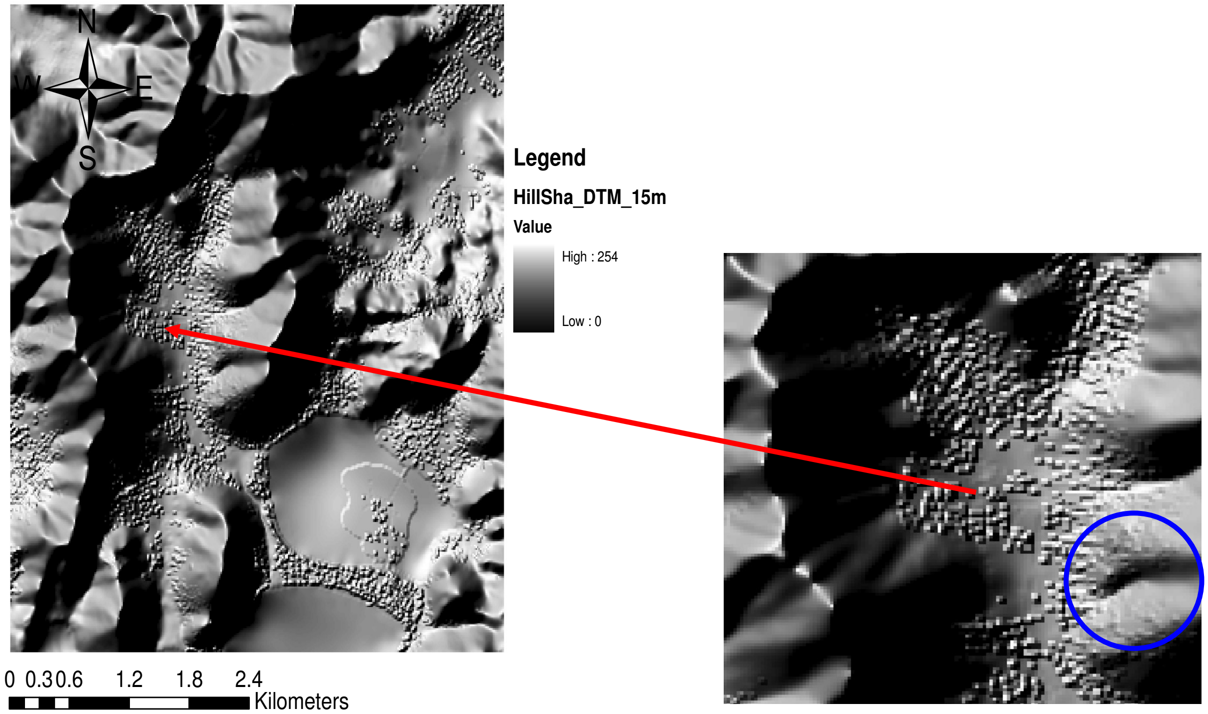

Figure 29: DTM with Smooth, Road network and Buildings- 15m Resolution

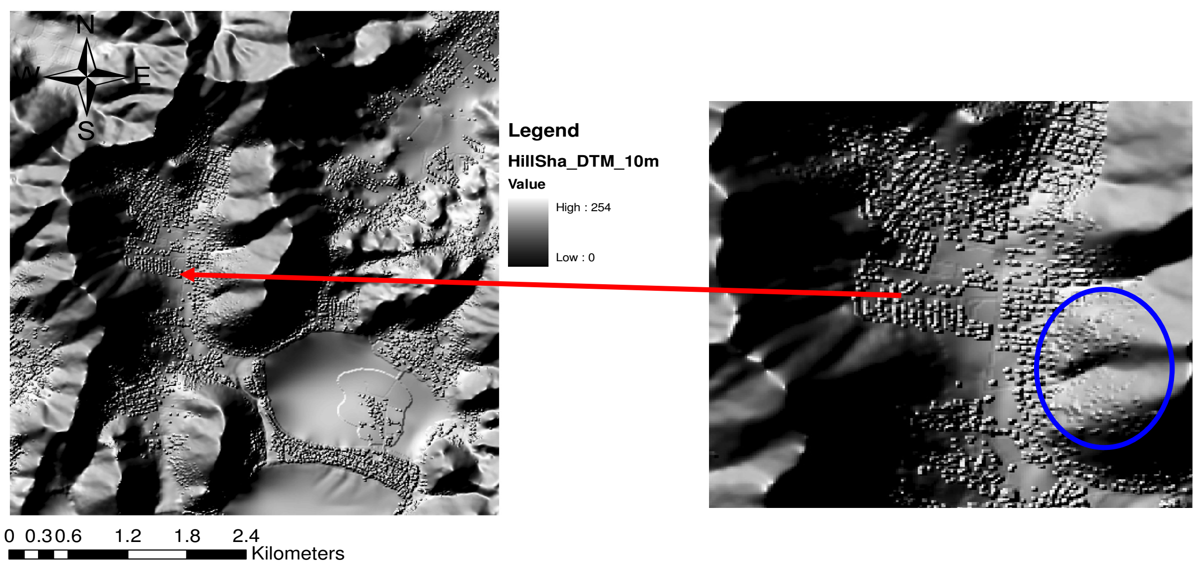

Figure 30: DTM with Smooth, Road network and Buildings- 10m Resolution

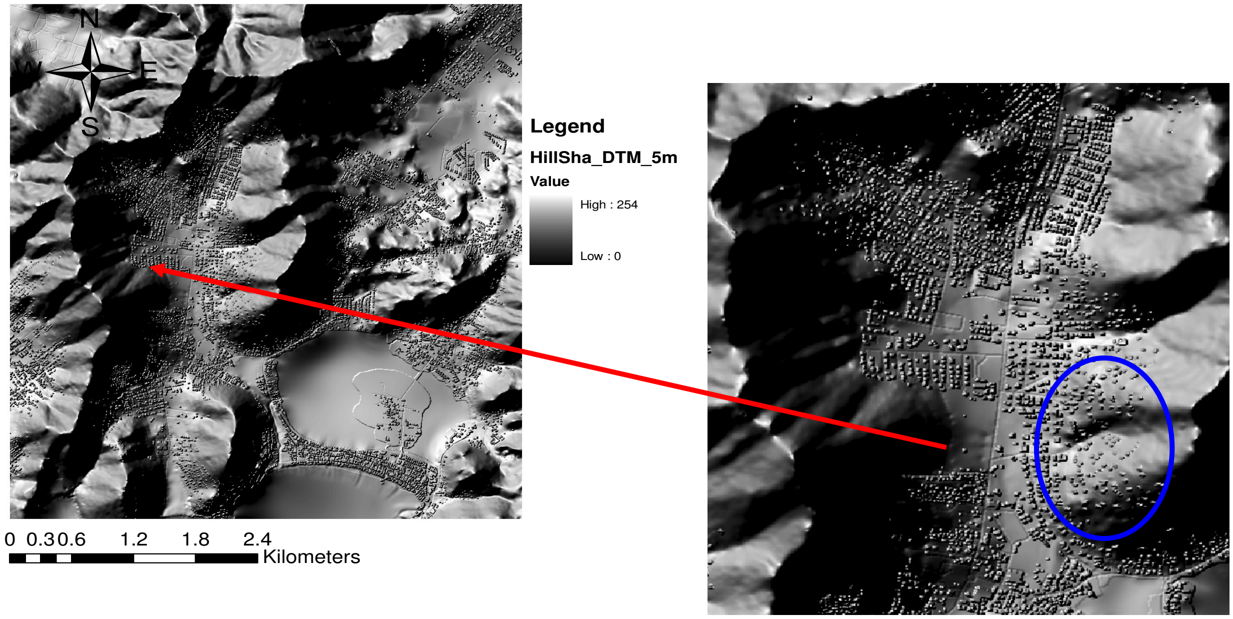

Figure 31: DTM with Smooth, Road network and Buildings- 5m Resolution

The blue circle shown in figures 28-31 shows example of an area where some of the houses were lost due to change of grid cells from 5m to 20m

4.5 Preparation of DTM for input to 2D models

Once the processing of DTM data was finalised, all the DTMs were then converted into ASC II raster format using ArcToolbox/Conversion Tools/from raster to ASCII of ArcGIS software. The 2D model (MIKE 21) accepts the terrain elevation in ASCII file format.

More details procedures in preparation of 2D models as DTM one of input data to the model is described in chapter 5 on Flood modelling.

5 FLOOD MODELLING

5.1 Introduction

The procedures for building a 1D and 2D hydrodynamic models including with data input and description of output results is described in this chapter. In this study the MIKE FLOOD (1D-2D) model was used for the flood modelling. MIKE FLOOD is the 1D-2D model combines one dimensional channel flow (MIKE11) with overland represented by a 2D grid of elevation information (MIKE21) into a single dynamically coupled modelling systems.

Using a coupled approach enables the best features of both a one-dimensional and two-dimensional models to be utilised, whilst at the same time avoiding many of the limitations of resolution and accuracy encountered when using MIKE11 and MIKE21 separately. MIKE 11 and MIKE 21 were firstly prepared before building MIKEFLOOD. In the MIKE11 same network as used from previous study (Tutulic', 2007) was adopted in this research. The main adjustment made was the cross section, whereby the cross sections were changed to V-shapes for research purposes. The same channel depth was used for all Digital Terrain Models with resolutions 20m, 15m, 10m and 5m.

5.2 Building 2D Model-MIKE21 Flow Model

In preparing the 2D model, all the necessary parameters inside the MIKE 21 model were set, so that the model could be ready for coupling and running. The basic parameters and Hydrodynamic parameters were involved in setting up theMIKE21 model.

Within Basic Parameters, the model selection, Bathymetry, Simulation Period, Boundary and Flood and Dry options was performed. While Initial Surface Elevation, Boundary, Source and sink, Eddy Viscosity, Resistance and Results, options were performed within Hydrodynamic Parameters.

5.2.1 Basic Parameters

The following basic parameters for MIKE 21 Flow Model simulation were performed.

5.2.1.1 Model Selection

Hydrodynamic only (the HD module alone) was selected in this model. It is a full non-linear equation of continuity and conservation of momentum.

5.2.1.2 Bathymetry

The first step and by far the most important task in a modelling process were setting up the bathymetry model. The main element of 2D MIKE 21 model is the digital terrain model (DTM), which represents the numerical value of the surface topography. The topography has to represent all the detail of urban topography such as streets and buildings. This is because the main utility that can be provided by adding this model to 1D model is to add the information of flow on surface during urban flooding.

The bathymetry was prepared using an option of making a MIKE 2D grid (.dfs2 file) found in MIKE Zero features from ascii file prepared in ArcMap. Different bathymetry with digital terrain model resolutions of 20m, 15m, 10m and 5m was prepared in different geometries i.e. Land with smooth surface only, land with smooth surface plus Roads and land with smooth surface, roads and buildings. The bathymetry prepared for DTM with 20, 15m, 10m and 5m resolutions are as shown in figure 32, 33, 34 and 35 respectively.

The MIKE 21 flow model requires information about the number of dynamically nested grids to be applied in the simulation. The maximum number of nested areas is 9. The first area, area number 1, is referred to as the "main area". But in this case there is only one main grid to work with. There is option to start a simulation in two different ways:

- as a cold start or
- as a hot start.

For a cold start the velocity field is initialized to zero. The hot start facility requires a hot file for each area. These must originate from a previous simulation. The hot start files contain all necessary information to continue a simulation. In this way simulation time can be reduced if for instance a number of scenarios are to be compared, all based on the same (hot start) initial conditions. In this research the cold start option was selected.

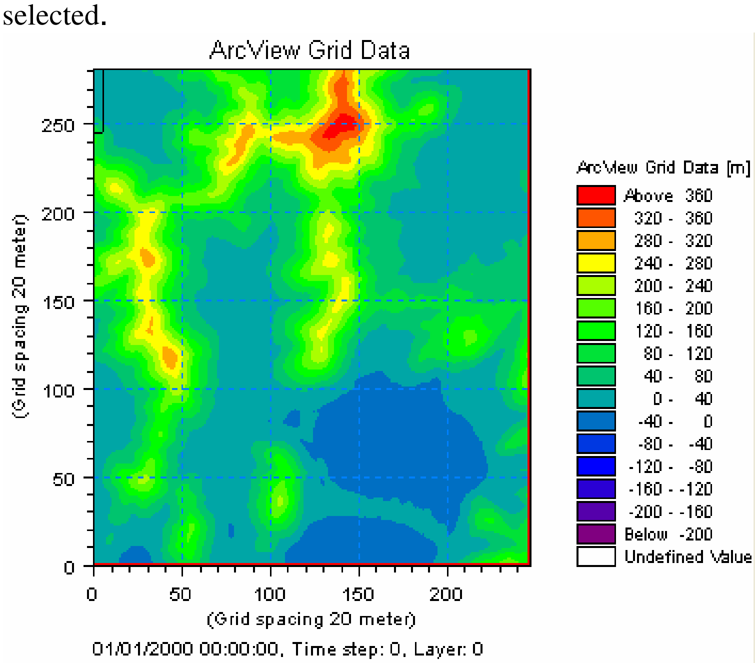

Figure 32: Bathymetry Prepared for MIKE21-DTM 20m resolution

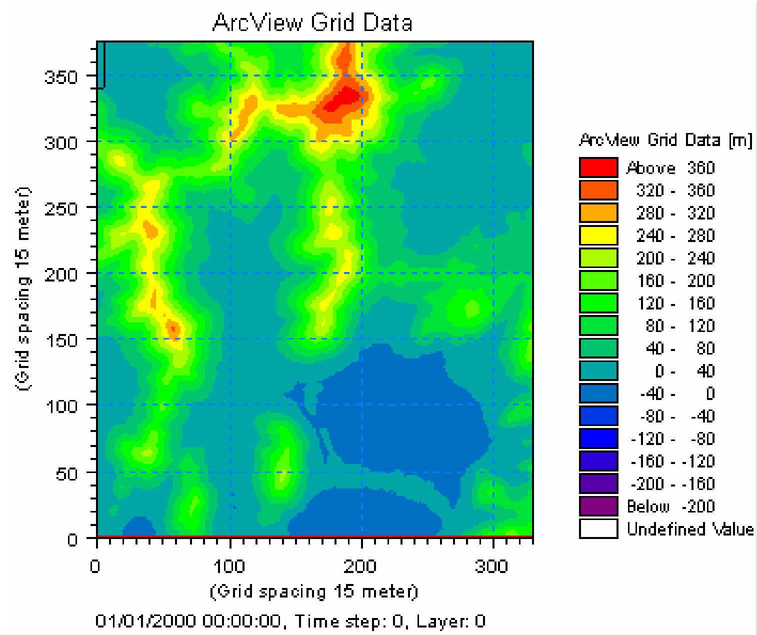

Figure 33: Bathymetry Prepared for MIKE21-DTM 15m resolution

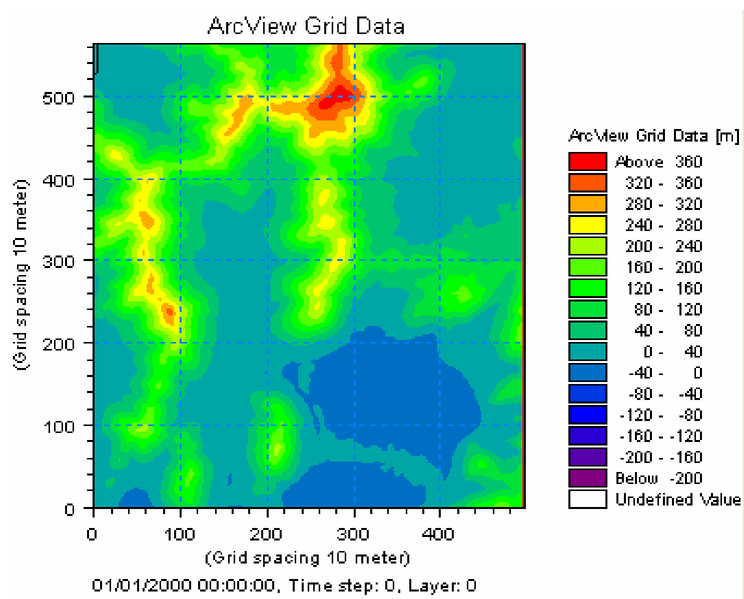

Figure 34: Bathymetry Prepared for MIKE21-DTM 10m resolution

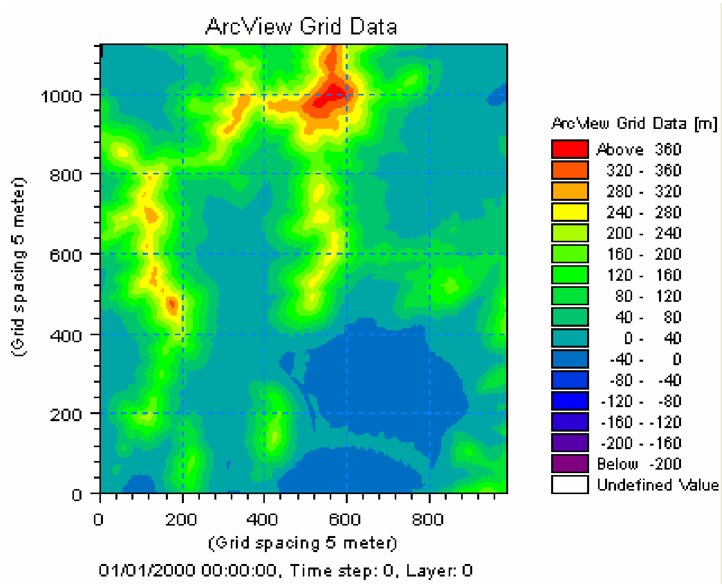

Figure 35: Bathymetry Prepared for MIKE21-DTM 5m resolution

5.2.1.3 Simulation Period

Information on simulation period was provided. Time step range is the number of time steps the simulation should cover. The time step interval is the value for which the time is incremented between each time step (equal for all areas). The simulation start date is the historical date and time corresponding to time step zero. The warm-up period is a number of time steps over which the forcing functions are gradually increased from zero to 100% of their true value. The simulation period was specified with suitable time step keeping stability of the model in mind. In this study, time step was chosen to be 1 s and the simulation period was set to be 30 June 2005 from 12 till 18 hours.

5.2.1.4 Boundary

The boundaries of the models are closed since no flow is assumed into and out of the model area. So, the boundaries were assigned with high land value, which represent the true land and act as walls. A value representing land means that all grid points with a depth value equal to or greater than the land value will always be considered to be land and will not be subject to possible flooding and drying. In this study, the boundary conditions were set to Program Detected option. The program selects the boundaries automatically which can be changed if needed.

5.2.1.5 Flood and Dry

In case of urban flooding it may occur that some reach of a street become dry for some time and may get water again after sometime. To take care of this, flooding and drying depths are defined in this section. This is done to set the minimum water depth allowed in a point before it is taken out of calculation (drying depth), and also the water depth at which the point will be re-entered into the calculation (flooding depth). In this study these depths have been set to 0.002 and 0.003 m respectively.

5.2.2 Hydrodynamic Parameters

The following Hydrodynamic parameters MIKE 21 Flow Model simulation were performed

5.2.2.1 Initial Surface Elevation

Having selected a cold start simulation under Bathymetry, information about the initial surface (water) level was also to be provided. The initial surface elevation for each area can be specified in two ways:

- as a constant value for the respective area or
- to be read from a 2D (.dfs2) data file.

Most often the initial surface level can be set to a constant value to be applied over the whole model area. This means that the simulation will start out with the surface level raised accordingly.

In this study, where there are two ponds downstream (Fresh Pond and Great Salt Pond), the initial surface elevation file for the two ponds was prepared in ArcMap to set up the initial water level on the ground with different values.

5.2.2.2 Boundary

All the boundary data were supplied here for the boundaries defined in the earlier section. As discussed earlier, the choice of variation at an open boundary can be either level or flux (the flux is the total amount of discharge passing the open boundary).
Actual values, level or flux, at each boundary can be specified in one of five different formats: a constant value, a sine series, a time series, a line series and transfer data.
Since the boundaries within Basic Parameters were set to be detected by the program, all settings inside this part were automatically set up by the program itself. It is important to note that while deciding and applying boundary conditions in MIKE 21 model the grid itself implies that the open boundaries must be positioned parallel to one of the coordinate axes (this is not a fundamental property of a finite difference scheme but it is essential when using MIKE 21 HD). Furthermore, as per the manual of the MIKE 21 supplied by DHI, the best results can be expected when the flow is approximately perpendicular to the boundary. This requirement may already be in contradiction with the above mentioned grid requirements, and may also be in contradiction with "nature" in the sense that flow directions at the boundary can be highly variable so that, for instance "360" flow directions occur, in which case the boundary is a most unfortunate choice. However the same normal flow could have been achieved during model running also.

Two primary boundary conditions of flux and water level, for MIKE 21 HD module must be given at all the grid points and at all the time steps. Due to space staggered scheme the values of the flux densities at the boundary are set half a grid point inside the topographical boundary.

Being a 2D model, MIKE 21 needs secondary boundary conditions also. This is chosen because it coincides conveniently with the fact that the simplified MIKE 21 HD, the