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Professional Practice Report

Analysis of the Complete Water Cycle for Flood Modelling in Mixed-Urban Areas through Coupled Hydrological-Hydraulic Modelling with MOUSE-Mike SHE

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Abstract:

Urban flooding is a serious problem worldwide and its management and control has commanded the intense efforts of engineers and professionals throughout the history of water resources management. In this age of information and communications technology, computer modelling tools have become widely used in the field of stormwater management and improved methods are continuously being developed. The state of the art in urban flood modelling is the use of a coupled hydraulic pipe (1D) and overland (2D) model that is able to accurately represent flow through the drainage networks and, at the same time runoff following the topography as well as the dynamic exchange of water between the two systems. However, this modelling procedure is limited by situations when dynamic catchment hydrology is an important factor in the occurrence of flooding in the area as it does not take into account the realistic movement of water through the entire water cycle. A new generation of urban flood modelling procedure which takes into account the processes in the whole hydrological cycle is required for mixed-urban areas, and the evolution of urban areas and emergence of green cities further highlight this need.

In this project, the development and use of a coupled hydrologic-hydraulic model (MOUSE-Mike SHE) for simulating flooding in a mixed-urban area were investigated, and the method was also compared to the state of the art procedure of using a coupled 1D-2D hydraulic model (MOUSE-Mike 21). A step-by-step procedure for building a MOUSE-Mike SHE model was developed during the study which answered the need for documentation for how to go about the process as current versions of the software do not have features for straightforward coupling of the two models.

Simulation results showed that the MOUSE-Mike SHE modelling method shows great promise as a new generation of urban flood modelling technique that is more holistic and adaptable to a wider range of hydrological conditions. The model is able to realistically describe the occurrence and movement of water over the land surface—accumulating in areas of natural channels and flowing according to the terrain and around structures. However, discrepancies between simulated results and observations necessitate further development of the method ensuring that: actual conditions in terms of physical system characteristics and correct boundary inputs and conditions in the study area are reproduced as closely as possible; a correct level of detail is used that gives a good balance between accuracy and computational effort; and that calibration of model parameters is performed.

Key-Words: **Urban flood modelling, Flood, Mixed-Urban Catchments, Hydrological Modelling, 1D-2D modelling, Stormwater management**

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1. INTRODUCTION

Urban flooding is well-recognized as a very serious problem worldwide. It adversely impacts a great concentration of the population and disrupts major economic activities in an area, and its negative effects may persist long after its occurrence. Inadequate capacities of drainage systems are a common cause of urban flooding. Thus, stormwater management has generally developed along the lines of continuously increasing the effectiveness of drainage systems in evacuating water away from the area and the population as fast as possible through installation, rehabilitation or upgrading, and expansion of drainage structures—building bigger and more extensive networks and detention facilities in an attempt to cope with the increasing incidence of devastating flood events. Fast-developing information technology tools have also been greatly utilized in implementing solutions for stormwater management. Computer modelling as an efficient and technically sound tool for developing strategies and making decisions has found widespread use in the industry and flood modelling has become an essential component of management systems for most urban areas around the world.

Traditional modelling techniques, primarily using 1D fully dynamic pipe network models, effectively represent conventional urban stormwater management systems. Over the years, increased computer power has also made the use of 2D models for accurately describing complex overland flows during flooding more practicable. Nevertheless, their overall cost-effectiveness is still limited and with continuous improvements in 1D modelling techniques the use of the relatively more simplistic 1D method remains popular and widespread. In order to utilize the effectiveness of improved 1D models and the recognized accuracy of 2D models, methods that dynamically couple 1D and 2D models have emerged and have achieved great promise in accurately describing floods even in areas of complex terrain.

The most current method for urban flood modelling is the use of a coupled hydraulic pipe (1D) and overland (2D) model, which takes advantage of improved computing capabilities of the time and gives more accurate representations of the physical processes in the system. It is able to accurately represent flow through the drainage networks and, at the same time, runoff following the topography as well as the dynamic exchange of water between the two layers could be accurately represented. This methodology works very well for areas that are highly built-up because it is expected that stormwater flows are largely characterized by runoff from impervious surfaces and through the drainage networks. However, the performance of this type of coupled 1D-2D flood model for areas that comprise of combined impervious and green areas is limited. Hydrological processes such as infiltration into the ground and flow exchanges between groundwater and surface waters should be considered in describing water drainage and flooding in these types of catchments.

The increasing popularity of the use of green areas in alleviating flooding requires new modelling procedures that have a more integrated approach in the analysis of the movement of water through the system. The altered surface and hydrological characteristics of "green" cities will require a flood modelling method that considers all the major processes in the hydrological cycle.

A 2D physically-based distributed hydrological model as a component of a new flood modelling method has the great possibility of giving better results compared to previously-used traditional procedures. This 2D model that is able to simulate the whole water cycle, including overland flow, infiltration, and groundwater flow, used together with a 1D pipe network model could produce a powerful new tool for accurately simulating flooding in mixed-urban areas because of its greater capacity in realistically describing total water movement in the system. It will be able to simulate not only surface runoff from impervious areas but also account for the exchange of water between the drainage system and groundwater. Moreover, the model would be applicable for a wide variety of land surface conditions, and thus, can be adapted to different areas and settings. It will be able to simulate the important processes of the water cycle for places with extensive green areas, but at the same time, if the area being analyzed is highly-built up, the hydrological processes that become unimportant can be easily disregarded.

And so, for this professional practice project, the use of a coupled hydrologic-hydraulic model (MOUSE-Mike SHE) for simulating flooding in a mixed-urban area is investigated and evaluated against the state-of-the-art procedure of using a coupled 1D-2D hydraulic model (MOUSE-Mike 21). This study will contribute to the development of a new generation of flood modelling procedure which answers the need for a simulation technique that realistically reflects all the important hydrological processes in catchments with significant amounts of green areas.

1.1. Objectives

The objectives of the project are:

- To develop a step-by-step procedure for building a MOUSE-Mike SHE model for flood modelling which has not been explicitly documented before.
- To document and evaluate the use of Terrain Datasets in ArcGIS as a more efficient method of generating DTMs (Digital Terrain Models) for urban flood models from massive amounts of point elevation data.
- To implement the flood modelling approach that considers the complete urban water cycle (MOUSE-Mike SHE) to more properly simulate flooding events for a combination rural-mixed-urban area.
- To investigate and compare the use of the MOUSE-Mike SHE modelling approach to the MOUSE-Mike 21 methodology for hydrologic and flood modelling in a mixed-urban area through examination and evaluation of the differences in model setup requirements, system descriptions, and results, and to be able to explain the reasons for these differences.

1.2. Methodology

The project will be performed within the context of the 2BG (Black, Blue and Green) and Urban Flood Projects at DHI, which entail the investigation of how the complete urban water cycle could be considered in flood modelling and stormwater management. There are essentially two study areas in this project with each corresponding to one of the last two objectives enumerated in Section 1.1. The study is conducted in two major parts:

- Implementation of MOUSE-Mike SHE (MMSHE) for the Olsbaekken catchment. MOUSE-Mike SHE models are built for the Olsbaekken catchment. One is a very detailed model of the highly-built-up lower catchment while the other is an overall model of the watershed. The detailed model is developed first with all the requirements and steps in building it noted down in detail. It is tested and corrected for errors before simulations attempting to recreate the flooding of 5 July 2007 in the study area are run using the model. The accuracy of the MMSHE model is then evaluated by comparing simulation results to available observations. Then, then overall model is built according to the steps developed for building an MMSHE model, and simulations are run to recreate the 5 July 2007 flood event. The results of the overall model are compared to those of the detailed model and their performance in simulating actual hydrological processes is evaluated.

- Comparison of Mike Flood and MOUSE-Mike SHE models for Greve Midt. The existing Mike Flood (MOUSE-Mike 21) model is prepared for comparison with the MMSHE model to be built for Greve Midt. The Greve Midt MMSHE model is prepared according to the previously outlined steps and also referring to the given Mike Flood model. Simulations using the same period and rainfall event are run and the results of the two models are compared to each other. The differences are identified and analyzed and the suitability of using MOUSE-Mike SHE to model urban flooding is evaluated.

Figure 1. below summarizes the methodology used in this study:

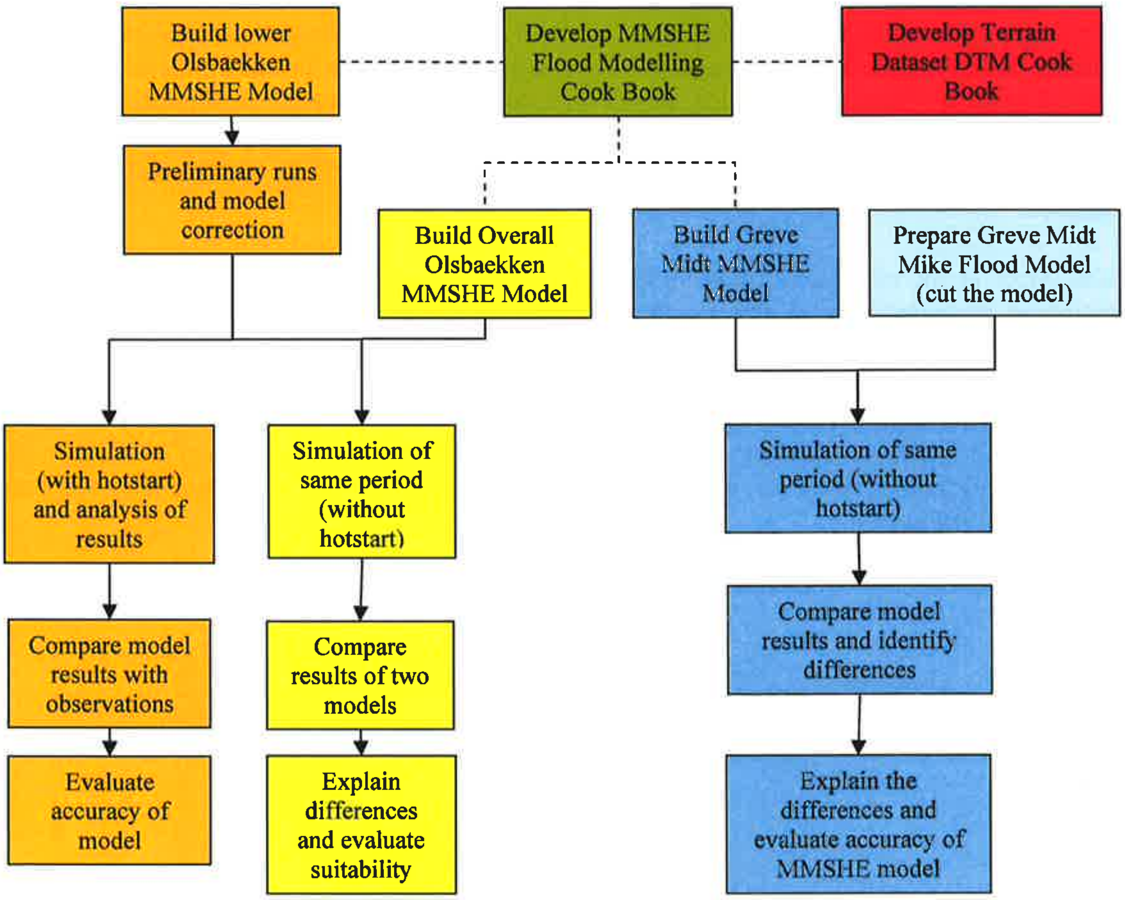


Figure 1. Methodology used for the study

A side-task in this project is the assessment of the use of Terrain Datasets in ArcGIS for developing a more efficient method of generating Digital Terrain Models (DTMs) for use in 2D overland models for flood modelling. The steps for this new method are documented alongside the development of the procedure for MMSHE models and included in this report in Appendix A. The Terrain Dataset method is also compared and evaluated against the traditional interpolation (IDW) method for generating DTMs.

2. MOUSE-MIKE SHE MODELLING

This chapter explains the technical background about MOUSE-Mike SHE (MMSHE) modelling. A procedure for building a coupled model for flood modelling purposes is also presented because a detailed documentation of the methodology is currently not available. The features for coupling the two models have been incorporated in the softwares but explicit and clear steps on how to build coupled models specific for use in flood modelling have not been drawn up although models for these types of applications have been developed and used for various projects within DHI.

2.1. Background

MOUSE (MOdeling of Urban SEwers) is an advanced and comprehensive numerical modeling system for urban drainage systems. It is capable of combining the processes of hydrology, hydraulics, water quality and sediment transport to simulate surface runoff, open channel flow, pipe flow, water quality and sediment transport in urban drainage and sewer systems analysis. The software has found wide application in the modelling of sewers and urban drainage around the world, and numerous papers have been published presenting principles and case studies about MOUSE that demonstrate its strong performance for these purposes.

Mike SHE is an integrated hydrological modelling system that allows one to trace the movement of water through the whole hydrologic cycle in an area. Mike SHE covers the major processes in the land phase of the hydrologic cycle such as evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions (Figure 2.). It has a flexible framework in that hydrological processes could be described independently within different modules such that, depending on specific conditions, significant processes may be selected and combined for more efficient and accurate modelling of the system.

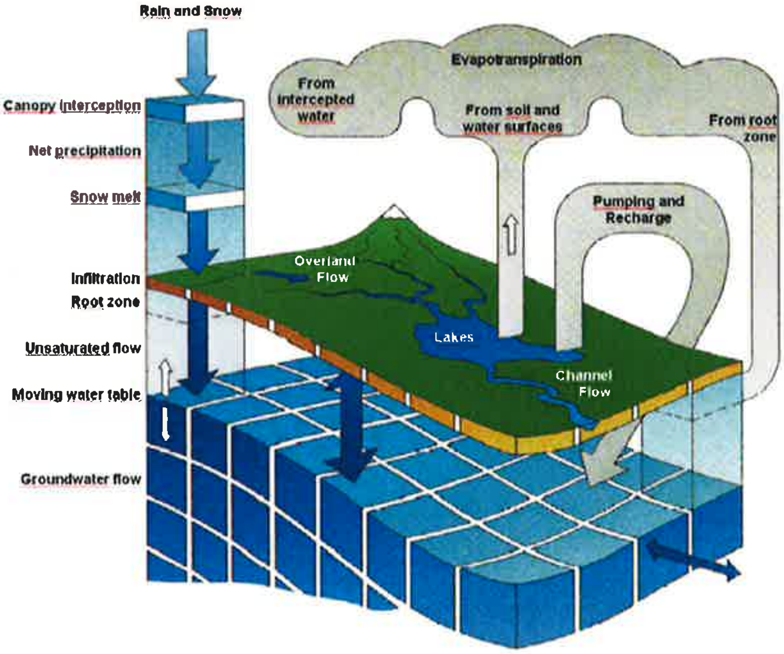


Figure 2. Hydrologic processes modelled in Mike SHE (Source: DHI, 2008c)

differently from Mike FLOOD in that the maximum elevation is considered correct. This allows the occurrence of manholes that protrude out of the ground.

The flow exchange between the sewer system and the land hydrology varies depending on the kind of link specified. There are five ways by which flow exchanges can occur between MOUSE and Mike SHE, and the distinction is made through the calculation of the exchange coefficient for each type (Figure 4.):

(1) *Mike SHE Saturated Zone to MOUSE links.* Flow exchanges (in both directions) can occur when the water table comes into contact with the drainage pipes. The exchange coefficient for this case is based on the surface area of the link that is in contact with the aquifer and the specified leakage properties of the pipe and the hydraulic conductivity of the aquifer.

(2) *Mike SHE Overland Flow to MOUSE links.* Open channels may be defined in MOUSE, and overland flow in Mike SHE can go into these open channels. For this case, the flow is considered as simple drainage throughout the channel length or as flow through a weir. Unlike when the model is coupled with Mike 11 links, Mike SHE overland flow can just flow over the MOUSE open channels.

(3) *Mike SHE Overland Flow to MOUSE Manholes.* Manholes may also not be sealed, and so water on the Mike SHE surface may go into the manholes and vice versa. The exchange coefficient may describe simple drainage or flow through a weir.

(4) *Mike SHE Saturated Zone Drain Flow to MOUSE Manholes.* Some structures in the study area, such as houses with basements, may have underground drains that prevent flooding due to seepage of water from underground. These may be designed to directly drain into the sewer network. To specify this flow exchange in Mike SHE, the drained areas and the specific MOUSE nodes that they drain into are identified. Drainage levels, or the elevation at which drainage begins for the structures are also specified.

(5) *Mike SHE Paved Areas to MOUSE Manholes.* Precipitation over paved areas that immediately goes into the drainage system may be specified in Mike SHE by identifying these regions and, similar to the saturated zone drain flow, specifying the MOUSE nodes that these areas drain into.

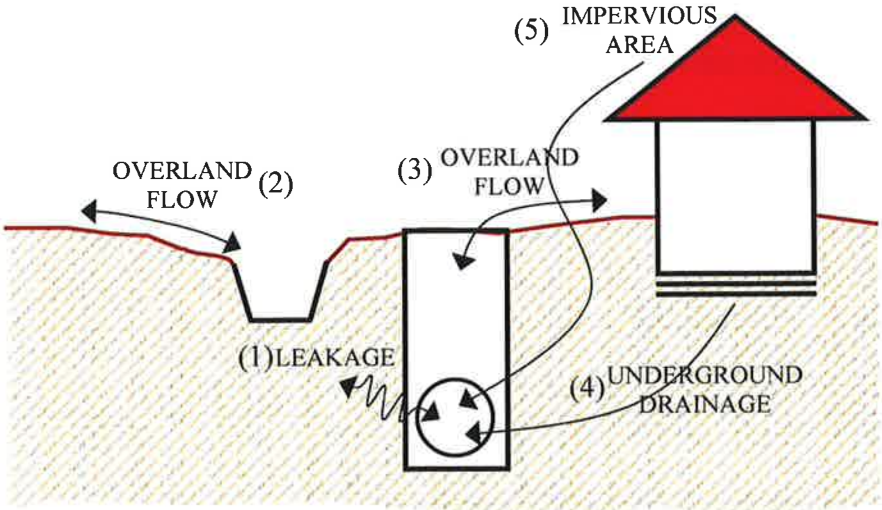


Figure 4. Flow exchanges between MOUSE and Mike SHE

To make a MOUSE-Mike SHE model, independent MOUSE and Mike SHE models for the study area must first be built. Then, the places where the two models interact are specified.

The interaction of surface and subsurface hydrology with the urban drainage network can be simulated with Mike SHE through establishing a link with MOUSE (Figure 3.).

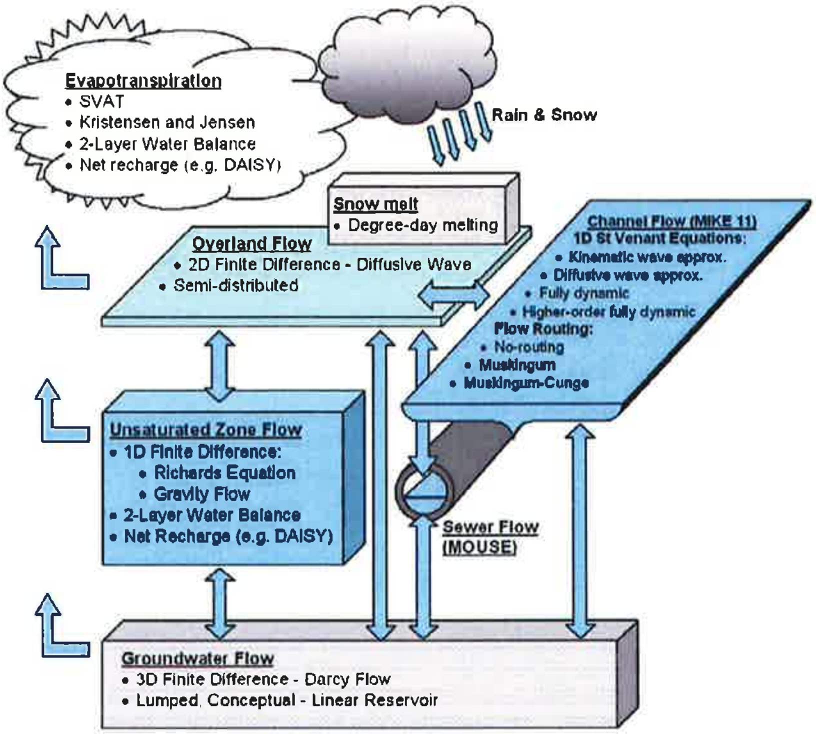


Figure 3. MOUSE may be coupled with Mike SHE (Source: DHI, 2008d)

Flows are exchanged between Mike SHE and MOUSE at specified linking points according to the difference in appropriate heads in the two systems and an exchange coefficient.

$$Q = C \cdot (H_{SHE} - H_{MOUSE})^k \qquad (1)$$

Where,

Q = flow exchange between MOUSE and Mike SHE
C = exchange coefficient
k = head different exponent

With,

$$H_{SHE} = Max(H_{cell}, Z_T, Z_M)$$

$$H_{MOUSE} = Max(H_{pipe}, Z_T, Z_M)$$

Where,

H_{cell} = head in Mike SHE cell
H_{pipe} = head in the MOUSE pipe
Z_T = topographic elevation in the cell
Z_M = top elevation of the manhole

This means that since the value for head used is the highest value among the hydraulic head, the land elevation, and the manhole top elevation, the software allows manhole top elevations to differ from the land elevation and that if the top elevation is much higher than the land level by mistake, flow exchange may be hindered between the two systems. The ground elevation differences between the Mike SHE topography and MOUSE nodes are treated

The latest version of Mike SHE (2008 version) does not have a clear interface for specifying the links and so special parameters in the models and separate coupling files must be generated.

The Mike SHE interface is used to run the coupled model. MOUSE is called from Mike SHE to perform a time step until the end of the Mike SHE time step has been reached. The MOUSE model runs normally as if it is launched directly from MOUSE.

2.2. Data Requirements

The following table summarizes the kind of data that may be needed when building a MOUSE-Mike SHE model:

Table 1 - Data needed for MOUSE-Mike SHE model

Climate Data: • Rainfall/precipitation – station data (rain gauge data) • Temperature – station data; for calculating snow melt • Potential evapotranspiration – station data or calculated from meteorological data
Land Features Data: • Topography (preferably reflecting features such as buildings and roads) • Geological layers and their hydraulic conditions – for calculating groundwater flow • Groundwater abstractions • Unsaturated zone characteristics or soil distribution (soil profiles with characteristics, groundwater levels) • Land use and vegetation characteristics (cropping, root depth, leaf area index) • Drainage of rural areas • Rivers – MIKE11 or MOUSE
Drainage System Data: • Foundation drains information (levels, location) • Sewer network description • Leakage coefficients for links/pipes • Impervious area characteristics • Overland flow conductivities
Calibration Data: • Flow measurements • Groundwater level observations • Surface water level

2.3. Model Set-up

This section describes the procedure for building a MOUSE-Mike SHE model. Some items are specific for modules that have been selected for this study but general steps are also explained in detail.

There are 3 basic steps in setting up a coupled MOUSE-Mike SHE model:

1. Establish a stand alone MOUSE hydraulic model, make a performance test and, if possible, a rough calibration
2. Establish a Mike SHE model that includes the modules that are expected to have a link with the drainage model (i.e. OL, SZ and UZ components)
3. Couple Mike SHE and MOUSE by defining the locations where MOUSE should interact with MIKE SHE.

In building a MOUSE-Mike SHE model, the major processes describing water movement and the relationships among the different processes must first be identified. For an urban flood model, runoff from built-up areas is collected by the drainage system, which consists of manholes, pipes, and open channels. When the drainage system is overwhelmed water flows out through manholes and channels onto the streets and overland, and then depending on flow conditions in both the drainage network and overland, will continue to flow overland or back into the drainage system.

2.3.1. Establishing the MOUSE Model

The MOUSE model for the drainage system will be used to simulate runoff from impervious areas and describe flow through pipes, manholes, basins, as well as the open channels that receive runoff in the study area. There has been a long history of the use of MOUSE software in urban stormwater management, and so it has been assumed that the use of the software is widely known. Thus, MOUSE modelling is not the main focus of this project report but instead more on procedures related to the Mike SHE model component.

Build the MOUSE model according to usual procedures ensuring that it has all the essential elements of the network and can properly represent the processes in the system (Figure 5.). Streams in the area should be represented in the MOUSE model using open channels with special cross sections. The percentage of impervious areas for each catchment must be determined as accurately as possible using information from GIS layer files because the total impervious area in MOUSE must correspond with that in Mike SHE to maintain correct water balance.

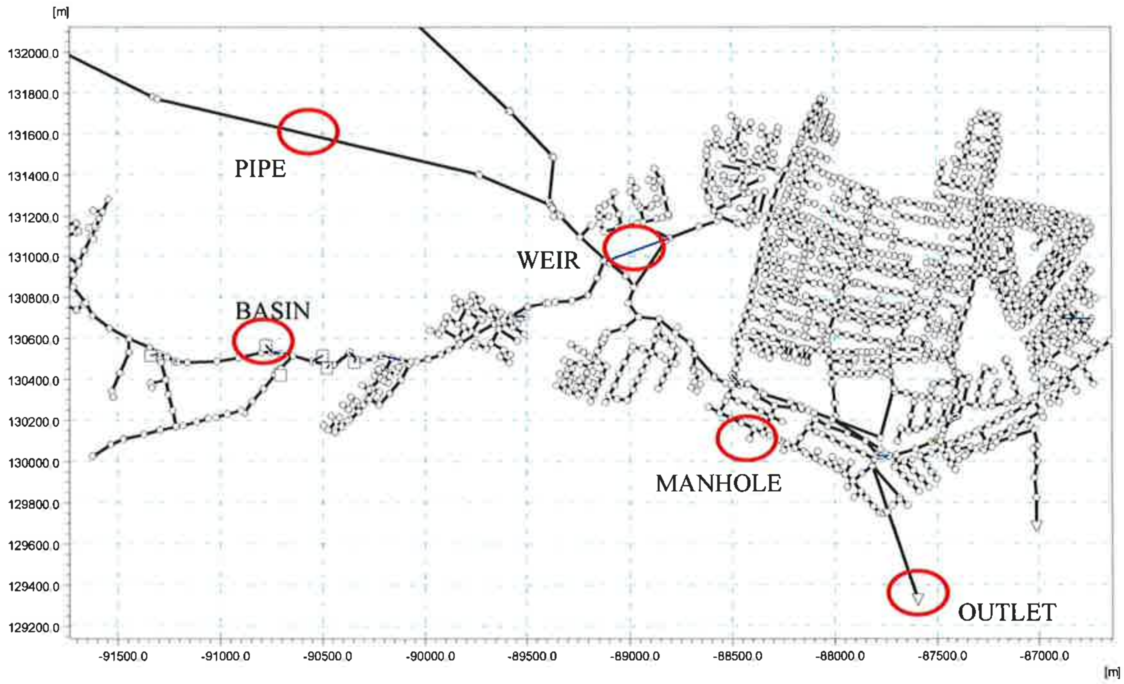


Figure 5. Example of a MOUSE model layout of drainage structures in an area

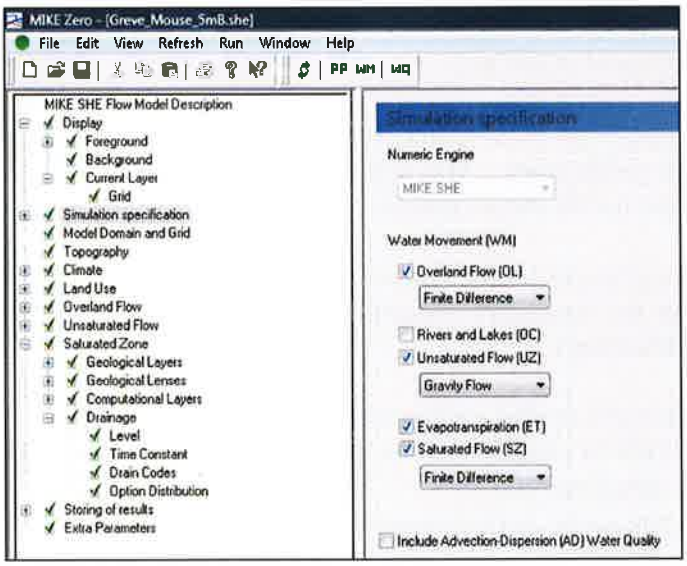
Make sure that the MOUSE model is valid by running simulations and checking error and warning messages. Ensure that the geometries of the elements in the network are correct such that, for example, none of the links have zero length. It is best if the layout of the drainage elements in MOUSE correspond well with their real positions with respect to the topography. Links with zero lengths will give an error in Mike SHE which, for the current version of the software, does not give an explicit error message and thus difficult to detect and debug.

2.3.2. Establishing the Mike SHE Model

Creating a Mike SHE model that is appropriate for coupling with a MOUSE model is described below. The procedure goes through the major sections of the Mike SHE Editor.

a) Define the Water Movement Modules

First, the hydrological processes that need to be included in the model must be specified in the "Simulation specification" window. The characteristics of the catchment dictate the processes that must be selected.



Numeric Engine: MIKE SHE

Water Movement (WM)

☑ Overland Flow (OL): Finite Difference

☐ Rivers and Lakes (OC)

☑ Unsaturated Flow (UZ): Gravity Flow

☑ Evapotranspiration (ET)

☑ Saturated Flow (SZ): Finite Difference

☐ Include Advection-Dispersion (AD) Water Quality

Figure 6. Main hydrological components of a MOUSE-Mike SHE flood model

The water movement modules that may be activated are the following:

- *Overland Flow (OL).* Water accumulates on the ground surface when net rainfall exceeds the infiltration capacity of the soil. This water is then available for surface runoff, which flows according to the topography and surface roughness and usually eventually drains into the rivers. The Finite Difference Scheme for the OL module calculates overland flow using the diffusive wave approximation of the Saint Venant Equations.
- *Rivers and Lakes (OC).* This module allows for the description of the interaction of surface water bodies with the groundwater and overland flow in Mike SHE when the bodies of water are described by a Mike 11 model. It is activated when a coupled Mike 11-Mike SHE model is desired.
- *Unsaturated Flow (UZ).* Unsaturated flow describes the variations in soil moisture (just below the ground and above the water table) according to rainfall infiltration and evapotranspiration and recharge to the groundwater. When antecedent soil moisture conditions significantly influence flow peaks, a relatively detailed view of the unsaturated zone is desired (showing actual evapotranspiration, infiltration, and recharge to the groundwater). However, a full view of the dynamics in the zone may not be required, and the Gravity Flow option for the UZ module may be appropriate—less complex than the

full Richards Equation and yet more accurate and descriptive than the 2-Layer Water Balance Method.

- *Evapotranspiration (ET).* A big percentage of green areas demands for the inclusion of the ET module in the model. Evapotranspiration determines the amount of net rainfall that may comprise overland flow, and affects the amount of moisture in the soil and the amount that recharges the groundwater in the saturated zone.
- *Saturated Flow (SZ).* This module calculates 3D groundwater movement in a hetergoneous aquifer in the catchment. It is necessary if flow interaction with groundwater of the drainage network and natural channels in the study area is expected, such as when the groundwater table is shallow.

Data input trees are added to the Mike SHE Editor according to the processes specified during module selection. The succeeding sections explain the general inputs for items that comprise the model when the Overland, Unsaturated Zone, Evapotranspiration, and Saturated Zone modules have been activated.

b) Define Model Domain and Grid

The extent of the model must be identified based on the coverage of the MOUSE model and the urban catchment delineation. The sub-catchments that contain the relevant MOUSE nodes must be selected for the model domain.

Select an appropriate grid size for the model. It should be fine enough to be able to represent the terrain including the structures adequately and yet still within the software grid and computational cell limitations.

When defining the domain and the computational grid keep in mind that the software has the following practical limits to ensure that you will be within your computer's capacity:

- Cells in x- and y-direction: 700
- Computational cells per layer (incl. boundary cells): 125,000
- Number of computational saturated zone layers: 50
- Number of river links: 10,000
- Number of computational UZ columns (multi-layer UZ): 30,000
- Number of nodes per UZ column (multi-layer UZ): 150

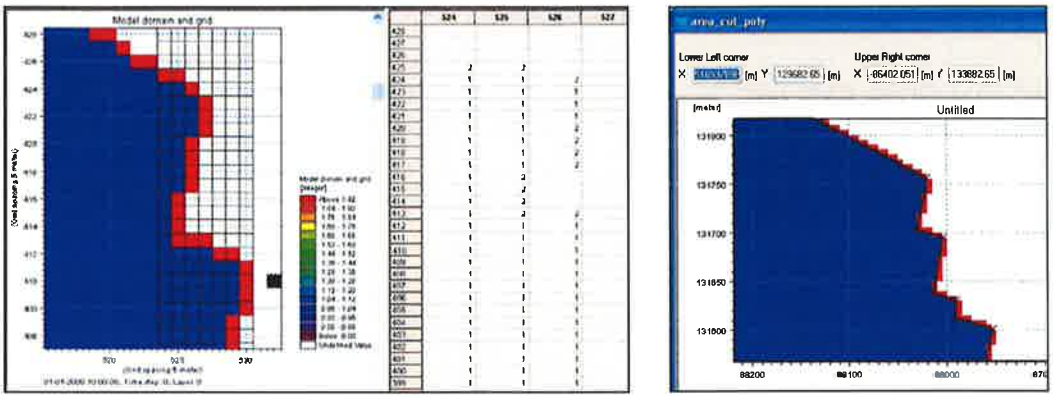
Increasing these limits may be necessary due to the level of detail that your analysis requires. This may be done by downloading and installing the latest Service Pack for Mike SHE/Mike Zero from the DHI website, which will extend the limits to the following:

- Cells in x- and y-direction: 1,000 x 1,000 (from 700 x 700)
- Computational cells per layer: 250,000 (from 125,000)
- UZ columns: 100,000 (from 30,000)
- River links: 20,000 (from 10,000)

Limits much higher than these may be requested, but before insisting the use of such a heavy model its practicability should be re-evaluated because you may run the risk of exhausting your computer's resources.

The model domain and grid can be defined by a DHI grid file (*.dfs2) or a GIS polygon shapefile (*.shp). Since it is more flexible in terms of adjusting the cell size and number of rows and columns, a polygon shapefile may be preferable. Note that polygon ZM shapes are not recognized by Mike SHE and need to be first converted to polygon shapes in Arc GIS before they can be used. Mike SHE eventually uses the shape to generate a DHI grid during Pre-processing wherein appropriate grid values are assigned for the different components of the domain, which are:

- Cells outside the domain = assigned delete values (i.e. -1e-35)
- Cells inside the domain = 1
- Cells defining the boundary = 2



Lower Left corner
X [illegible] (m) Y 129682.65 (m)
Upper Right corner
X -86402.051 (m) Y 133882.65 (m)

(a) Mike grid file for model domain (b) Shapefile for model domain

Figure 7. Two types of files for specifying model domain and grid in Mike SHE

The DHI grid from the pre-processed polygon shape file may then also be extracted and saved and then used as a domain grid in other models.

c) Define Topography

The topography defines the surface for overland flow in Mike SHE, and also the upper boundary of the "underground" model. The topography grid is usually developed from an ArcGIS DTM that is converted to a Mike grid using the Mike Zero Toolbox.

Since the MMSHE model is intended for use as an urban flood model, it is necessary that the structures (roads and buildings) are properly reflected in the topography. The movement of water around structures and "channel" flows along roads during floods could then be simulated.

It should be noted that when the buildings are reflected in the topography when using Mike SHE for flood modelling, the topography is used as a reference for underground components such as upper and lower levels of geological lenses, elevation of initial potential head, and drain levels.

The current procedure for generating a DTM involves interpolating values in between available x-y-z points representing the terrain using GIS software or Mike Zero. However the number of point values can reach millions for big and/or well-surveyed areas and traditional interpolation methods are not able to handle data of this amount. A new method for generating a DTM, which is able to easily handle a great amount of point data, was explored and the procedures are described in Appendix A. An evaluation of the performance of the method compared to the traditional IDW method of generating DTMs was conducted and presented in Chapter 4.

d) Specify Meteorological Conditions

Precipitation is added to the model by specifying its distribution and magnitude. The rainfall data could be time-varying but uniform over the area such that only one time series is used for the entire model area.

Because Mike SHE will be coupled with MOUSE, the precipitation must be spatially distributed according to "stations," which actually divide the area into whether rainfall falling on the surface goes into Mike SHE or into MOUSE.

Rainfall over paved areas may be assumed to first go into the drainage system. If rain over a certain area (i.e. paved areas) goes into MOUSE, that area is specified in Mike SHE as a place with zero rain. This is because that amount of rain is already considered in the MOUSE model. Given this, it should be ensured that the total excluded area in Mike SHE is equivalent to the runoff-contributing areas in MOUSE.

Evapotranspiration is assumed to be a significant process which must be considered in the model. As with precipitation, Reference Evapotranspiration (ET) is specified as time-varying and uniform over the entire area, but evapotranspiration over paved areas is disregarded. Evapotranspiration is considered to be significant only in green areas, and additional parameters for this process are further described in the Vegetation section of Land Use.

e) Specify Land Use Characteristics

The items on the land surface that affect the hydrology in the model area are defined in this step. The Paved Areas option may be activated to bring a part of overland flow to the drainage network. The distribution of different types of vegetation around the study area must be described. This information is used for quantifying evapotranspiration.

The area is subdivided into places with different combinations of vegetation and corresponding vegetation properties/evapotraspiration. The "Vegetation Editor" is used to specify vegetation data for the evapotranspiration and irrigation management modules. The vegetation database contains the time varying characteristics for each type of vegetation that is specified in the model domain. The database is optional and can be used only when the Evapotranspiration and Unsaturated Zone components are included in the model.

f) Define Overland Flow Boundaries and Conditions

It is expected that overland flow will occur over the surface following the topography. Flow resistance for the surface must be specified by assigning Manning M (1/n) values for various areas. The following table gives reference values for Manning M:

Table 2 - Manning roughness for various surfaces

Material	Typical Manning roughness coefficient (n)	Corresponding Manning M (1/n)
Concrete	0.012	83
Gravel bottom with sides		
- concrete	0.020	50
- mortared stone	0.023	43
- riprap	0.033	30

Material	Typical Manning roughness coefficient (n)	Corresponding Manning M (1/n)
Natural stream channels		
– Clean, straight stream	0.030	33
– Clean, winding stream	0.040	25
– Winding with weeds and pools	0.050	20
– With heavy brush and timber	0.100	10
Flood Plains		
– Pasture	0.035	29
– Field crops	0.040	25
– Light brush and weeds	0.050	20
– Dense brush	0.070	14
– Dense trees	0.100	10

(Source: Chow, 1959)

g) Specify Unsaturated Flow Conditions

Precipitation over unpaved areas infiltrates into the soil and could interact with the saturated zone (groundwater table) below. The water that infiltrates goes through the unsaturated zone and recharges the groundwater table or could also be removed from the layer through evapotranspiration. The unsaturated zone is usually made up of soil layers of different characteristics, and its moisture content varies dynamically as it is replenished by rainfall or drained by evapotranspiration or recharge to the saturated zone. Gravity is the primary force in unsaturated flow, and so the process can be described as generally vertical. Unsaturated flow is calculated only vertically in one-dimension in Mike SHE, which is sufficient for most applications.

There are three options to describe unsaturated flow in Mike SHE:
- Richards equation
- Gravity flow
- Two-layer water balance

The characteristics and distribution of different soil types in the study area must be described in the model. The regions are classified according to the general type of soil, with each general type comprised of different combinations of soil types with specific characteristics and layer thicknesses.

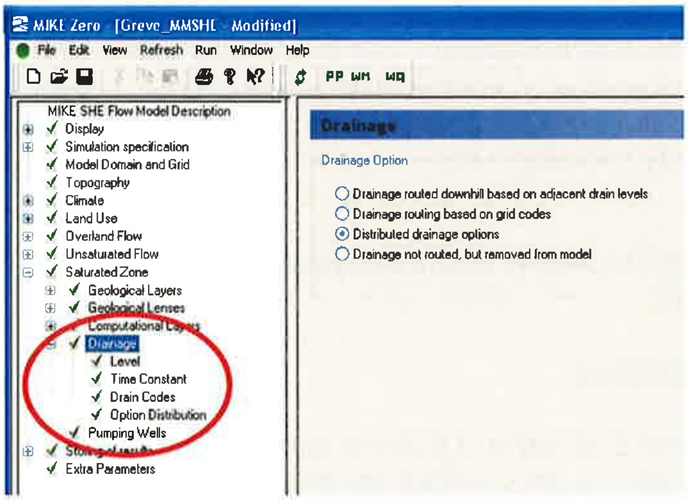
The grid cells and layers for UZ computation are classified according to specified soil types, vegetation, climatic zones, and depth to the groundwater table to form subsets of grid squares in order to reduce computation times. "Automatic" classification for the unsaturated zone lets the model do the classification based on the given parameters, but classifications may also be specified by the modeller if detailed computations are desired for certain areas. It may be desirable to choose a "Partial Automatic" classification, which is a combination of "Automatic" classification and "Specified" classification, in order to obtain detailed computations for certain areas that are deemed important but still keep the computation as efficient as possible. This option may be specified after initial runs with the "Automatic" classification and specify computations in areas where surface ponding were observed from initial results.

h) Specify Saturated Flow/Groundwater Conditions

This is where the subsurface geologic model (aquifer layers) is described in order to reflect the interaction of groundwater with surface waters and the drainage system. Digital maps of the layers with information about their important hydrologic parameters, such as layer elevations and hydraulic conductivities, are essential.

The different geologic layers and lenses must be described, specifying geologic parameters such as hydraulic conductivity, specific yield, and specified storage for each. Information about groundwater pumping could also be given in the model. The time series for this should cover the simulation period, but only for wells that fall within the model domain. The function of this section, essentially, is to remove water from the saturated zone.

Removal of water from the saturated zone could also occur if some structures in the model area, such as houses with basements, have artificial underground drainage. When groundwater levels reach specified drain levels water is removed from the saturated zone and, for this case, routed to the drainage network. Specifying the inputs for the Drainage section in the Saturated Zone module is one of the most involved processes in building the Mike SHE model. The next step below describes the procedure in accomplishing this in detail.



Drainage Option

○ Drainage routed downhill based on adjacent drain levels
○ Drainage routing based on grid codes
● Distributed drainage options
○ Drainage not routed, but removed from model

Figure 8. Saturated Zone module Drainage section in Mike SHE

i) Describe Saturated Zone Drainage

"Distributed drainage options" must be selected under "Drainage Option" when Mike SHE is coupled with MOUSE which adds additional items to the "Drainage" data tree. When SZ drainage is described as distributed according to drainage options, the grid cells are categorized and given appropriate codes depending on how and where they drain into. It is suggested to start with "Option Distribution" and work up to "Level" in completing the "Drainage" input.

- *Option Distribution.* An integer grid code distribution that indicates drainage options in different areas of the model and which says how areas in the domain are drained (underground) must be specified.

  It is very helpful to have a raster/ grid file showing the drained areas (buildings and sports fields) but distinguishing between them such that they have difference values/grid codes. This basic grid file will be useful in generating subsequent grid files needed in the section because it is important that the different grids exactly correspond to each other (in terms of extent/coverage). To ensure this, the shapefiles from which the rasters are generated must be exactly the same. Alternatively, subsequent grids that need to be specified may be built based on grids that have been specified earlier in the model. For example, select the buildings from the grid used for rainfall distribution (in the "Climate" section) showing built up areas (buildings, roads, parking lots) by saving the grid as a different file and removing the unwanted areas. Add the grid for the sports fields to the buildings grid. This may be done by loading a selection of the sports fields grid into the buildings grid. Assign different values for the buildings and sports fields to distinguish between the two. This basic grid can then be used to generate the other grids needed in the succeeding sections.

The option distribution grid may have the following values:
- Code = 1: Drainage in grid cells with a value of 1 is routed downhill based on the value of the drain level specified in Drain Level data item. It is typically used in forests, agricultural areas and surrounding areas with tile drains or small open ditches which are not included in the surface water system description.
- Code = 2: Drainage in grid cells with a value of 2 is routed via Drain Codes as specified in the Drain Codes data item
- Code = 3: Drainage in grid cells with a value of 3 is routed to a specified MIKE 11 branch and chainage (Mike SHE-Mike 11 coupling). At the moment, this option requires the use of Extra Parameters. Codes 2 and 3 are typically used if the drainage is more controlled than in Code 1 areas and with known specific drainage outlets.
- Code = 4: Drainage in grid cells with a value of 4 is routed to a specified MOUSE manhole. At the moment, this option requires the use of Extra Parameters. Typically this value is specified for parking lots, buildings with surrounding drains, stadiums and other areas draining to the system.

- *Drain Codes*. Assigning Drain Codes is the most involved task in this section. All areas with an option distribution code equal to 4 and 2 have to be further distributed by the drain code file so that flow can be routed to MOUSE. The drain codes must be assigned only to cells corresponding to the drained structures. The destination of drain flow into MOUSE is described in the PFS file, which links the drain codes with node (manhole) names.

  The identification of structures and areas that drain to MOUSE could be better facilitated if one has a polyline shapefile of the urban catchments in the study area. First, open the grid file for the drained structures/zones. Overlay the shapefile (polyline) for the urban sub-catchments. Then, assign unique values to drained areas inside each sub-catchment (using the Select, Deselect, and Set Value tools in Mike Zero). Within each sub-basin the drain code in grids with option code 4 should be identical. Begin for instance from 11 and count forward. Alternatively, polygon shapefiles of the subcatchments in ArcGIS may be assigned values corresponding to intended drain codes then converted to raster (of appropriate grid size) and finally to Mike grid. The drained zones may be loaded into the sub-catchment grid (Load Selection tool in Mike). A uniform value may then be added to this loaded selection in order to clearly distinguish them from the undrained zones, which could then be assigned delete values. The non-delete values may be returned to their original values (corresponding to the drain codes) by subtracting the uniform amount that was previously added to them.

In areas where the drain option code is 1, 2 or 3 the drain codes also determine where drainage water will go. If the drainage routing is specified by Drain Codes, a grid code map is required that is used to link the drain flow producing cells to recipient grid cells. The drain levels are still used to calculate the amount of drain flow produced in each node, but the routing is based only on the code values in the drain code file. The Drain Code can be any integer value, but the different values have the following special meanings:

- Code = 0: Grid cells with a Drain Code value of zero will not produce any drain flow and will not receive any drain flow. This was the value assigned to the grid cells with an Option Distribution value of 2 in the model, which means that there will be saturated flow drainage over these areas outside of buildings and sports fields.
- Code > 0: Grid cells with positive Drain Code values will drain to the nearest river, boundary or local depression in the drain level - in that priority - located next to a cell with the same Drain Code value. Thus, if a grid cell produces drainage, if there are one or more cells with the same drain code next to a river link, then the drain flow will be routed to the nearest of these cells; or if there are no cells with the same Drain Code located next to a river link, then the drain flow will be routed to the nearest boundary cell with the same Drain Code value; or finally, if there are no boundary cells with the same Drain Code value, the drain flow will be routed to the cell with the lowest drain level that has the same Drain Code value (which may create a lake).
- Code < 0: Grid cells with negative Drain Code values will drain to either a boundary or a local depression, in that order. Thus, if a grid cell produces drainage, if there are no cells with the same Drain Code located next to a river link, then the drain flow will be routed to the nearest boundary cell with the same Drain Code value; or if there are no boundary cells with the same Drain Code value, the drain flow will be routed to the cell with the lowest drain level that has the same Drain Code value (which may create a lake).

One method that is often used is to specify only one Drain Code for the entire model area (e.g. Drain Code 1). Thus, all grids can drain and any drain flow is routed to the nearest river link. If there are no rivers, the drain flow will be routed to the nearest boundary. If you want to route all drain flow to the boundaries instead of the rivers, a negative drain code can be specified for the entire area (e.g. Drain Code -1).

After assigning drain codes to drained structures, identify the receiving MOUSE nodes within each subcatchment/drain code area. Typically, this node can be identified from the MOUSE model as one of the major collection manholes downstream in the sub-basin, but choosing the exact receiving manhole is not very crucial. Build the ADP file based on the drain codes and manholes.

- *Time Constant.* The drain time constant (C_{dr}) determines how fast saturated zone drainage occurs. Drain flow is calculated as groundwater head above drain level times the drain time constant. As a rough estimate one can say that $1/C_{dr}$ determines the number of days for drainage. Typical values for tile drains are 1-2e-7 s^{-1} and for surround drains 1e-5 s^{-1}.

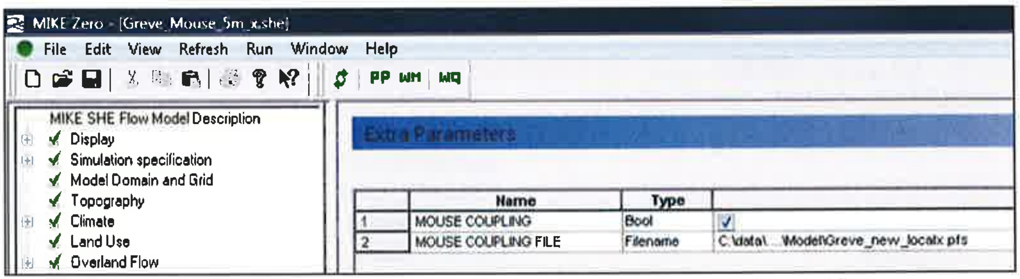
Different time constants must be specified for buildings and the sports fields. Time constants for buildings are higher indicating that drainage from these zones is better facilitated than from sports fields. Typical values for drainage rates are 1e-5 for houses and 2e-7 for sports fields.

- *Level.* The drain levels specify the elevation at which the groundwater begins to drain to the drainage system. It should correspond to the actual level of tile drains, surround drains around houses, bottom of drain ditches etc. Typically, levels are given as depth above ground surface meaning that the numbers given should be negative. Houses with basements will typically have a drain level at about -2 m and tile drains are typically -1 m. Swedish standards use: 0.7 m for houses without basements; 1.7-2.0 m for houses with basements; and 1-1.5 m for sports fields.

  However, drain levels are referred to the ground elevation in the topography, and so the heights of the buildings must be considered such that a drain level for a particular building must be its height plus the selected level below the ground. Considering building heights in determining drain levels is easy to do if the structures are given the same heights (i.e. 30 m) in creating the topography grid. If, however, the true heights of the buildings are reflected, making the Drain Level grid would be more involved. First, the heights of the buildings must be determined, perhaps through raster calculator in ArcGIS. Then, generate a Mike grid from the raster showing the building heights. Add the desired level (i.e. 2 m.) to the building heights in Mike Zero, and make the values negative to indicate that they are below the ground surface. Load the grid selection for the sports fields and assign the desired level (also negative) for these cells.

j) Give Extra Parameters

The Extra Parameters section contains the information about coupling Mike SHE and MOUSE.



	Name	Type	
1	MOUSE COUPLING	Bool	☑
2	MOUSE COUPLING FILE	Filename	C:\data\...\Model\Greve_new_localx.pfs

Figure 9. Extra Parameters section where the coupling is specified

A PFS file must be given and it should be ensured that the path to the file is correct. This PFS file tells Mike SHE that it is coupled to a MOUSE model. Details about the coupling and procedures for preparing the required files can be found in Section 2.2.3. (Coupling the MOUSE and Mike SHE Models).

2.3.3. Coupling the MOUSE and Mike SHE Models

The following figure illustrates the relationships between files and models that make up a MMSHE model.

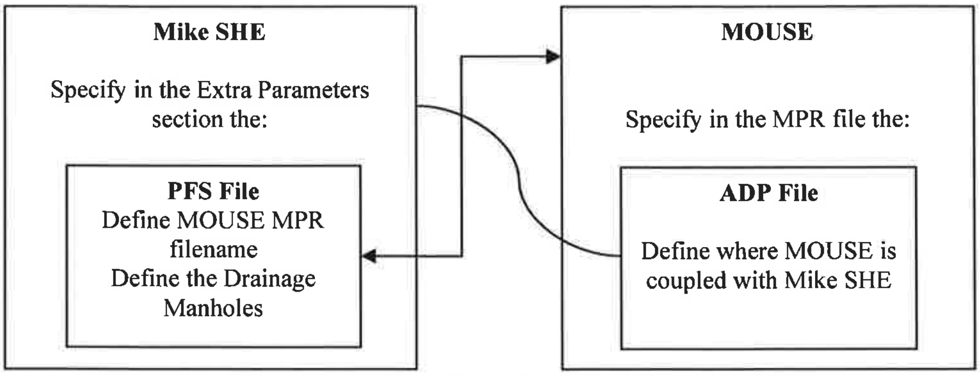


Figure 10. Illustration of coupling Mike SHE and MOUSE

The currently used (February 2008) version of Mike SHE does not have a well-defined interface for coupling with MOUSE, and so creating an MMSHE model is not quite straightforward. The following steps must be performed to couple the two models:

a) Create a PFS (*.pfs) file to define where and how the two models are coupled. The PFS file is an ASCII file that is divided into sections and contains all the information for the MOUSE-Mike SHE coupling. The file has a certain format and it is extremely useful if an old PFS file is used as a base for a new one.

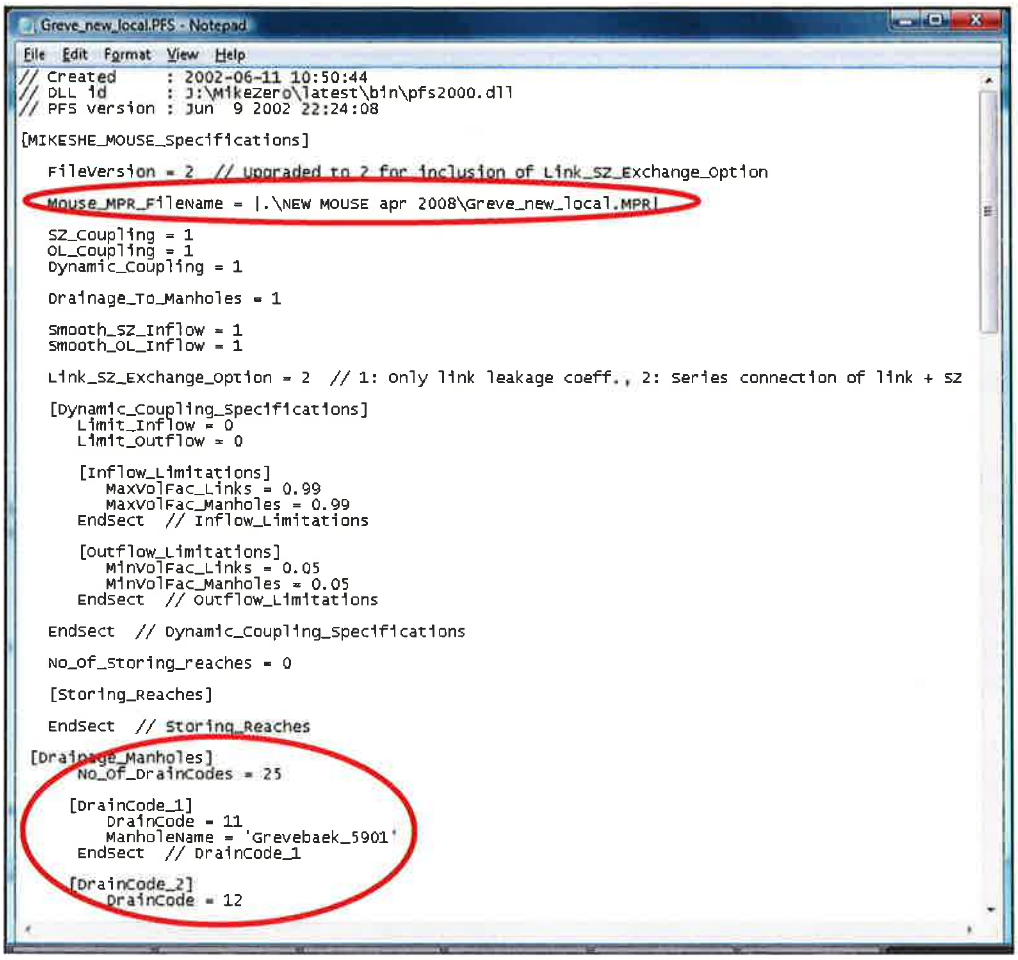
There are essentially 4 sections in the PFS file: (1) general specifications about the 2 models; (2) dynamic coupling specifications; (3) storing reaches description; and (4) information about drainage manholes. Details about the PFS files for the MMSHE models in the study are summarized in the table below:

Table 3 - MMSHE model PFS file items and descriptions

Item	Description
[MIKESHE_MOUSE_Specifications]	
FileVersion = 2	The file version indicates that coupling through the saturated zone has been included (Link_SZ_Exchange_Option)
Mouse_MPR_file name = |.\New MOUSE May 2008 (modif)\Import_V5_modif.MPR|	Name of the MOUSE mpr file. The MIKE Zero file name format (| |) indicates that the file name is relative to the location of this (PFS) document
SZ_Coupling = 1	Include SZ↔MOUSE coupling
OL_Coupling = 1	Include Overland↔MOUSE coupling
Dynamic_Coupling = 1	Dynamic coupling
Drainage_To_Manholes = 1	Include SZ (and paved area) drainage to manholes. In this case the SZ drainage option must be Levels and Codes. In the areas with drainage to MOUSE the Distributed Option code must be 4. For each Drain Code value in areas with Option Distribution 4 a reference from the code to a MOUSE manhole must be defined in the Drainage_Manholes section in this PFS file.
Smooth_SZ_Inflow = 1 Smooth_OL_Inflow = 1	Ensures a more smooth calculation of flows to MOUSE when the MIKE SHE time steps are large compared to the MOUSE time step. The MOUSE coupling is only made at every integer multiple of the MIKE SHE time step. If the Smooth option is not activated, the flows to MOUSE can stop after a number of MOUSE time steps because the

Item	Description
	calculated flow volume exceeds the volume of the MIKE SHE SZ/Overland grid cells. The Smooth option tries to use a reduced flow rate which equals the available volume/coupling time.
Link_SZ_Exchange_Option = 2	Indicates that leakage coefficient will be based on a series connection of the MOUSE pipe leakage coefficient and the MIKE SHE aquifer properties
[Dynamic_Coupling_Specifications]	
Limit_Inflow = 0	Inflow to MOUSE not limited
Limit_Outflow = 0	Outflow from MOUSE not limited
[Inflow_Limitations] MaxVolFac_Links = 0.99 MaxVolFac_Manholes = 0.99 EndSect // Inflow_Limitations [Outflow_Limitations] MinVolFac_Links = 0.05 MinVolFac_Manholes = 0.05 EndSect // Outflow_Limitations	Specifies inflow and outflow fractions
EndSect // Dynamic_Coupling_Specifications	
[Storing_Reaches]	
No_Of_Storing_reaches = 0	No storing reaches
EndSect // Storing_Reaches	
[Drainage_Manholes]	
No_Of_DrainCodes = 25 [Draincode_1] Draincode= 11 ManholeName='Greve_5901' Endsect // Draincode_1 . . . Endsect // Draincode_25	The manholes where saturated zones under areas with Option Distribution codes equal to 4 drain into are defined in this section. Make sure that the manhole names are the same as the codes in the MOUSE file.
EndSect // Drainage_Manholes	
EndSect // MIKESHE_MOUSE_Specifications	

When creating a PFS file for a new MMSHE model the two main sections that should be checked are the name of the MOUSE MPR file and the list of the Drainage Manholes and corresponding codes at the end.



```
// Created      : 2002-06-11 10:50:44
// DLL id       : J:\MikeZero\latest\bin\pfs2000.dll
// PFS version : Jun  9 2002 22:24:08

[MIKESHE_MOUSE_Specifications]

   FileVersion = 2  // Upgraded to 2 for inclusion of Link_SZ_Exchange_Option

   Mouse_MPR_FileName = |.\NEW MOUSE apr 2008\Greve_new_local.MPR|

   SZ_Coupling = 1
   OL_Coupling = 1
   Dynamic_Coupling = 1

   Drainage_To_Manholes = 1

   Smooth_SZ_Inflow = 1
   Smooth_OL_Inflow = 1

   Link_SZ_Exchange_Option = 2  // 1: Only link leakage coeff., 2: Series connection of link + SZ

   [Dynamic_Coupling_Specifications]
      Limit_Inflow = 0
      Limit_Outflow = 0

      [Inflow_Limitations]
         MaxVolFac_Links = 0.99
         MaxVolFac_Manholes = 0.99
      EndSect  // Inflow_Limitations

      [Outflow_Limitations]
         MinVolFac_Links = 0.05
         MinVolFac_Manholes = 0.05
      EndSect  // Outflow_Limitations

   EndSect  // Dynamic_Coupling_Specifications

   No_Of_Storing_reaches = 0

   [Storing_Reaches]

   EndSect  // Storing_Reaches

 [Drainage_Manholes]
      No_Of_DrainCodes = 25

     [DrainCode_1]
         DrainCode = 11
         ManholeName = 'Grevebaek_5901'
      EndSect  // DrainCode_1

     [DrainCode_2]
         DrainCode = 12
```

Figure 11. **Example of a PFS file with important sections highlighted**

b) Instruct Mike SHE to couple to a MOUSE model. This is done by specifying the PFS file in the “Extra Parameters” section of the Mike SHE setup editor. Make sure that the file paths and file names are correct.

c) Tell MOUSE that it is coupled to a Mike SHE model. This is done by specifying an ADP (Additional Parameter) file in the MOUSE model either through the hydrodynamic simulation window or by editing the MPR file using text editor.

For this project the ADP file only contains a section for the MOUSE Mike SHE Links. Details about the items in the file are summarized in the following table:

Table 4 - MMSHE model ADP file items and descriptions

Item	Description
[MOUSE_COUPLING] SYNTAX_VERSION = 1 UNIT_TYPE = 1 CALLER = 'MSHE'	Syntax Version = 1 indicates 2004 syntax version using SI units and the Unit Type must be given avalue of 1
// LineHeader = 'ID', 'LinkType', 'OLConductivity ','OLConductivityExponent', 'SzLeakageCoeff'	Comment line for headers for better understanding of the assigned values

// NODE
COUPLINGMMSHE= '34BA004', 1, 0.1,0.5, ,
.
.
	One line for each coupling item:
	ID = Link or manhole name/code
	LinkType = 1 for node; 2 for link (and ditches)

Item	Description

.
//LINK - Pipes
COUPLINGMMSHE= '34BA00411', 2, 0,0.5,0.00000000001
.
.
.
//LINK - Ditches
COUPLINGMMSHE= '34BA03611', 2, 0.1,1.5,0.00001
.
.
.
	OLConductivity = conductance for Overland flow to MOUSE, units depend on OLExp and whether it is a pipe or a manhole; No OLConductivity for closed pipes but exists for ditches
	SzLeakageCoeff = leakage coefficient; needed only when the saturated zone is coupled to a link; leakage into natural channels/ditches is easier than into pipes, so this value is higher for ditches

[Endsect]	

The coupling items describe how the calculations of flow exchange between the two models are performed. The assigned values for each type of link are explained in the following section:

Nodes:

- Link Type = 1 → Because it is a node
- Overland Conductivity = 0.1
- Overland Conductivity Exponent = 0.5
- Saturated Zone Leakage Coefficient = none → No flow exchange between saturated zone and manholes assumed

Links (Pipes):

- Link Type = 2 → Because it is a pipe link (with a length)
- Overland Conductivity = 0 → Flow cannot occur from overland directly into pipes
- Overland Conductivity Exponent = 0.5 → Assigned value does not matter
- Saturated Zone Leakage Coefficient = 0.00000000001 → Indicates very slow flow exchange between the ground and the pipes which are assumed to be in good condition

Links (Ditches/Natural Channels):

- Link Type = 2 →Because it is a "pipe" link (with a length)
- Overland Conductivity = 0.1
- Overland Conductivity Exponent = 1.5 → Describes weir flow
- Saturated Zone Leakage Coefficient = 0.00001 → Higher flow exchange rates between the ground and the natural channels

Considering that the flow exchange between the overland cell and the manhole can be described by the Bernoulli Equation:

$$H = k\frac{v^2}{2g} \tag{2}$$

Where,

H = head difference (m)
k = entrance loss coefficient
v = velocity (m/s)
g = gravity (m/s^2)

The flow would be given by:

$$Q = Av = A\sqrt{\frac{2g}{k}H} \qquad (3)$$

Where,
Q = flow (m^3/s)
A = area (m^2)

If the above equation is presented in the form of the flow exchange equation between MOUSE and Mike SHE:

$$Q = C\sqrt{H} \qquad (4)$$

Where,
C = flow exchange coefficient

The head difference, H, has an exponent of ½ and the exchange coefficient, C, includes other variables such as gravity and manhole area together with the loss coefficient.

An exchange coefficient exponent of 1 describes a simple drain formulation, but if the exponent is 1.5, then this is a weir formulation. Thus, for open channels, a weir formulation has been deemed more appropriate and the exchange coefficient exponent was set to 1.5.

For this study, the Saturated Zone Leakage Coefficient was set as a function of the both the hydraulic conductivity of the soil around the pipes and the pipe leakage properties. The hydraulic conductivity indicates the ease with which water can flow through the soil. For example, loose, coarse uniform soils have a higher conductivity than compacted soils with a range of particle sizes. Horizontal hydraulic conductivity values can range from as high as 0.001 m/s for loose, uniform coarse sand to 1×10^{-8} (0.00000001) m/s for tight, compacted clay. The vertical hydraulic conductivity is typically 5 to 10 times lower than the horizontal hydraulic conductivity. The initial estimates for SZ leakage coefficient of $1e^{-11}$ for pipes and $1e^{-5}$ for natural channel links are therefore reasonable.

d) Ensure that all the important MOUSE files in the MOUSE Bin folder (located in C:/Program Files/DHI/MOUSE) can be copied into the Mike Zero bin (located in C:/Program Files/DHI/MikeZero). Otherwise, when initializing the MOUSE coupling module when the MMSHE model is run, an error could occur saying that "Error code received from MOUSE dLL."

The reason for this could be that the mouse_hd.dLL file from the MOUSE Bin folder could not be properly copied into the Mike Zero bin folder. If this is the case, the mouse_hd.dLL file can be manually copied into the Mike Zero bin folder. Also, the batch file named CopyMOUSEFilesToMZ.bat in Mike Zero bin must contain the correct paths for copying of files. This can be checked by running the batch file and ensuring that all necessary files are successfully copied, or by opening it through text editor and checking the indicated file paths inside.

3. DESCRIPTION OF THE STUDY AREA

The modelling investigations were performed for two adjacent areas in the municipality of Greve in eastern Denmark which, for the project, were referred to as 1) Olsbaekken, and 2) Greve Midt.

Figure 12. Greve showing the two study areas (Olsbækken and Greve Midt). (Source: Google Earth)

Greve is a municipality in eastern Denmark along the eastern coast of the island of Zealand and is located about 20 kilometers south of Copenhagen. Essentially a suburb of Copenhagen, the municipality covers an area of about 60 square kilometers and is largely residential with a population of about 50000. It is an urban area that is quite densely built-up, especially along the coast. However, it also has a considerable amount of green areas especially in the upper catchments.

The city has had some serious flooding in the past, such as in 2002 and 2007. The flooding in 2002 was in the area Greve Midt – around the high school and the city hall. In 2007 the flooding in Greve Midt was avoided – but the Lower Olsbaekken area (Godsparken) was flooded due to unexpected runoff to the drainage system from fields upstream of the city. The municipality currently uses computer modelling as one of the major tools in the operation and management of its 50 kilometers of separate storm sewer network. They seek to greatly reduce the risk of flooding in the city even with the occurrence of climate change in the future.

3.1. Olsbaekken Catchment

The Olsbaekken is a combined rural-mixed-urban area. The upper catchment has big expanses of fields and green areas while the lower part is more built-up. An overall MOUSE-Mike SHE model was built for the whole catchment to determine overall hydrological conditions and a detailed model was built for the lower Olsbaekken catchment, which is the area located roughly to the east of the Køge Bugt Motorway up to the coast. Lower Olsbaekken has a relatively big amount of impervious areas and a dense drainage network including a natural stream running in the middle. A detailed model is needed for this area because it includes the places that were seriously flooded in July 2007.

3.2. Greve Midt

Greve Midt is the city center. It is highly built-up and densely populated. A flood model of Greve Midt using coupled MOUSE-Mike SHE was built and compared to an existing one that uses a more traditional MOUSE-Mike 21 (Mike Flood) modelling approach.

3.3. Flooding Problems in the Area

In August 2002 a 500-year rain event bringing 100 mm of rainfall over 3 hours inundated the area including the town center, and in July 2007 the city was once again struck by floods, this time due to a 20-year rain event. The rain which flooded the Olsbaekken area in 2007 was minimum a rain with a return period of 22 years – with is beyond the protection level in the Danish guide line: Skrift 27.

Although the drainage systems certainly complied with standards as they have been designed to withstand up to 10-year return period rain (according to Danish standards), they were overwhelmed by these extreme events. And so, in light of these floods, the city has decided to further reduce flood risks in the city and at the same time protect the area against potential impacts from flooding due to climate change. The city has made use of hydro-informatics tools and applied the latest knowledge about climate change to simulate the impacts from climate change and to upgrade the drainage systems accordingly. The city is currently in the process of designing new flood mitigation schemes, which will eliminate the impacts of climate change in the most economical way. New design rains according to a climate change scenario were applied to predict flood patterns for the city in 2100 using Mike FLOOD, which is a hydrodynamic modelling system that simultaneously simulates the flow in the sewers, surface flow and the flow exchange between the two systems.

4. GENERATING DTM USING TERRAIN DATASET IN ARCGIS

A DTM (Digital Terrain Model) is an essential component of a 2D overland flow model for flood modelling. Because of having to work with several DTMs during the study, a side-task that came about was the exploration of the use of the new Terrain Datasets feature in ArcGIS in order to more efficiently generate DTMs for flood modelling from great amounts of point elevation data. Around 50 million point elevation data spaced 1 m. apart for an area in Greve were used in this exercise.

4.1. Comparison of IDW and Terrain Dataset Methods

The traditional method of building a DTM is to use interpolation methods such as IDW (Inverse Distance Weighing) to generate information for spaces between available point data. This was attempted for the available dataset in this exercise, but 50 million points was too much and a DTM could not be generated. It was found that TIN generation using IDW has a practical limit of 15-20 million points (2 GB of memory per process in Windows Win32). On the other hand, a DTM was easily generated from the same dataset using the Terrain Dataset Method (as described in Appendix A) within 3 hours.

Table 5 - Comparison of limits for IDW and Terrain Dataset methods

	TIN by IDW	Terrain Dataset Method
Practical limits	15-20 million points	Billions of points (depending on the type of Geodatabase used)
Time to generate (using 50,786,870 points)	Unknown (interpolation was terminated after 8 hrs. elapsed)	~3 hours (including importing feature classes into geodatabase)

4.2. Evaluation of Terrain Dataset Method

To analyze the accuracy of the raster generated through the Terrain Dataset method (referred to as "Terrain-generated raster" hereinafter) the Raster Calculator tool in ArcGIS was used to determine if there were significant differences between the Terrain-generated raster and the IDW-interpolated raster.

The comparison focused on only a small part of the original dataset (that had 50 million points) so that a raster could be generated through the IDW method.

Figure 13. IDW-generated raster

Figure 14. Terrain-generated raster

Subtraction of the Terrain raster from the IDW raster showed significant differences between the two. The red regions in the figure below indicate "unacceptable" areas where the difference between the two rasters is more than 5 cm. Most of the areas with unacceptable differences were largely in regions without point values. The places where red areas intersect with points are especially unacceptable because the discrepancies are large despite the availability of point data. It was observed that these areas occurred in places where point data were irregularly spaced (such as along edges or gaps) and also where adjacent points had relatively big differences (>0.1 m) in z-values (steep slopes).

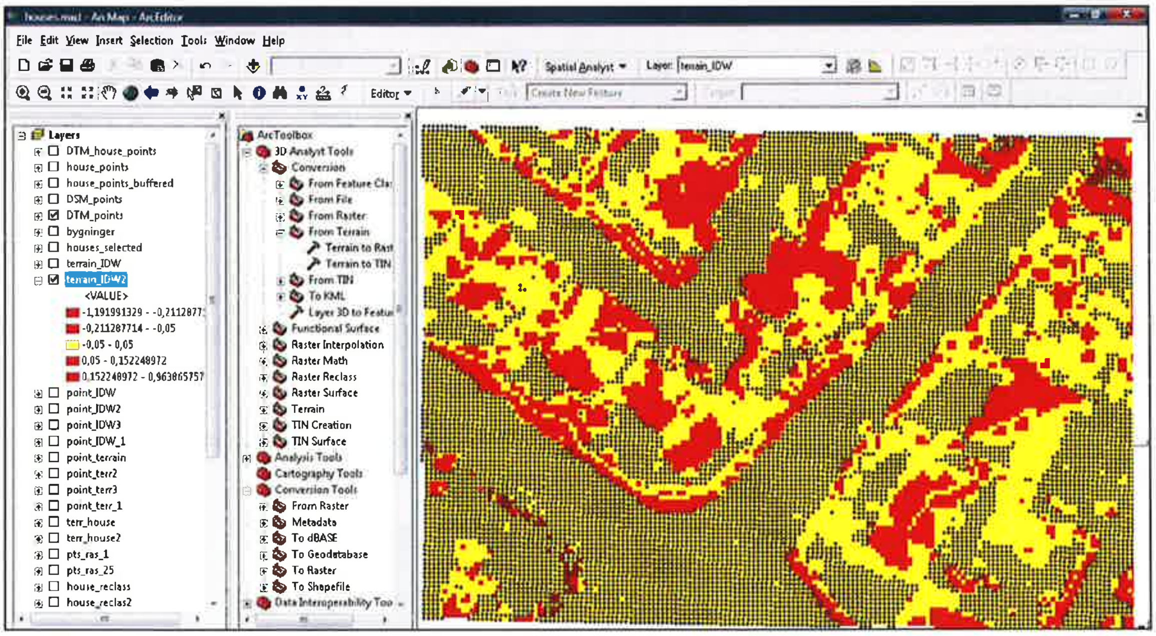


Figure 15. IDW-generated raster - terrain-generated raster

The significant differences (up to 1.2 m) between the Terrain and IDW rasters warranted a more detailed investigation of the discrepancy between the results of the two methods. A very small area was analyzed for the detailed comparison.

4.2.1. Detailed Analysis of the Terrain and IDW Rasters

There were point shapes averagely spaced at 1 m for the small area selected for the detailed analysis. Some areas were dense with points, while others were not. The point elevations ranged from 1.34 – 5.56 m.

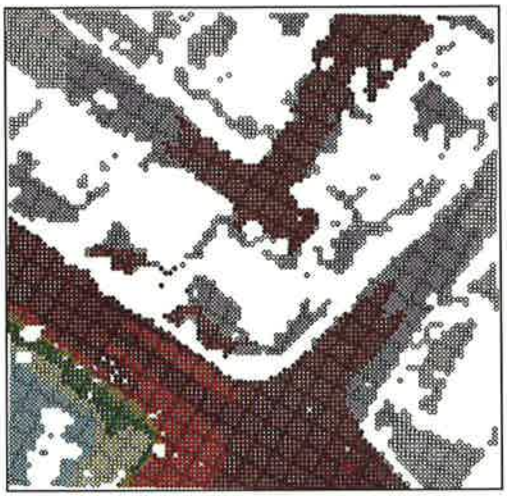


Figure 16. DTM point features for detailed analysis

A 1 m-grid raster was generated from the point shapes. The range of values for the resulting "Point raster" was 1.34 – 5.56m, which was the same as for the original point shapes. It was noted that the generated raster had the point elevations around the edges and not at the center of the cells.

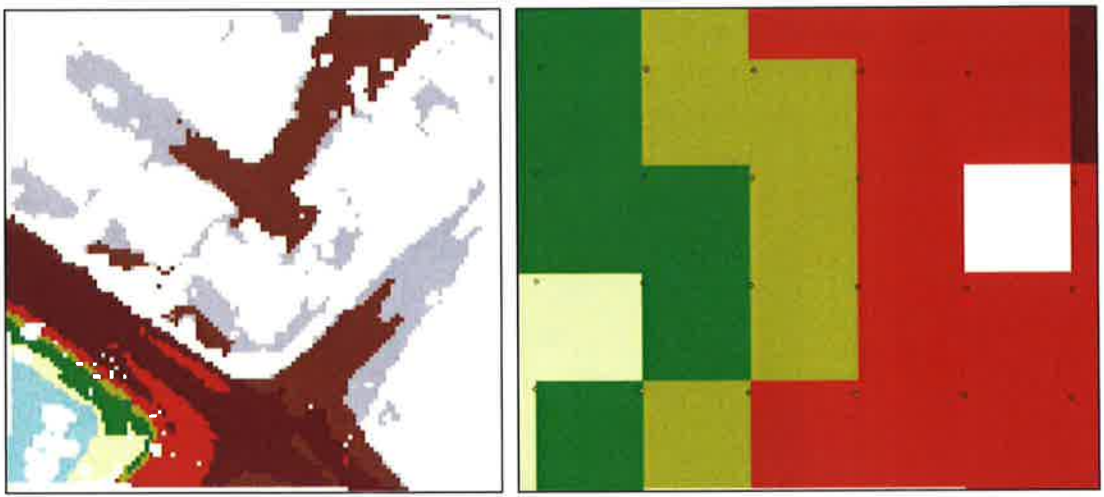


Figure 17. Point shapes interpolated into a raster (left) and a closer view of the raster showing the location of the point shapes (right)

A Terrain surface in TIN format was generated through the Terrain Method from the available 6958 point elevations. Its elevation ranged from 1.34 to 5.56m. The Terrain surface was then converted to a raster using the Linear interpolation method wherein the triangle encompassing a cell center is identified and a weighted average of the triangle's nodes is applied to interpolate the cell value. The resulting raster from the Terrain surface had elevations ranging from 1.37 to 5.54 m, which was slightly different from the range for the original Terrain surface.

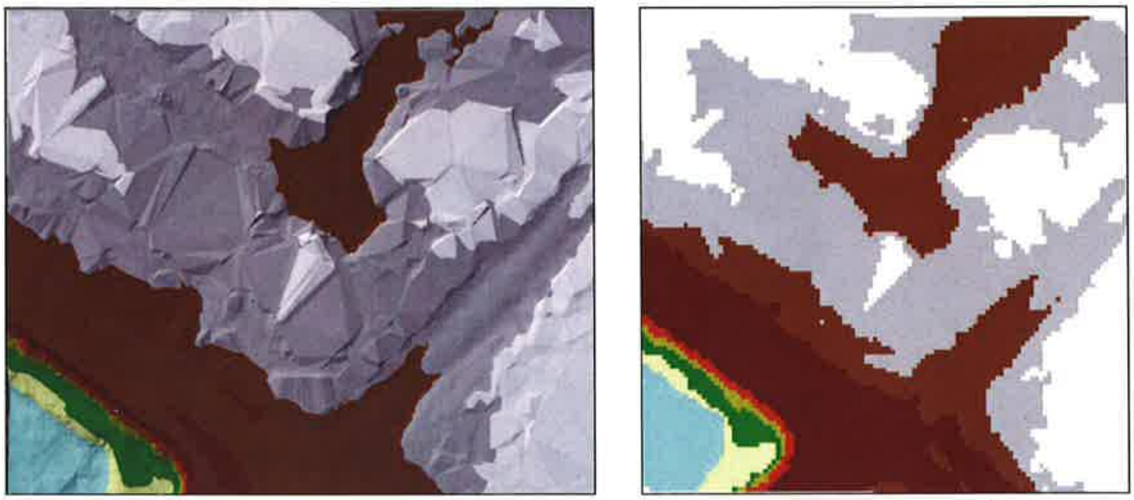


Figure 18. The generated Terrain surface (left) which was converted to raster (right)

A raster was also interpolated from the point elevations through the IDW method. This method predicts the value at a cell according to the nearby values weighed according to their distances to the cell being predicted. The IDW method, depending on the specifications, uses a greater number of points as source of information for interpolation, and a grid/raster is generated through this method in one step. For this analysis, the resulting raster had an elevation that ranged from 1.37 to 5.51 m, which was also different from the range of values for the original point shapes.

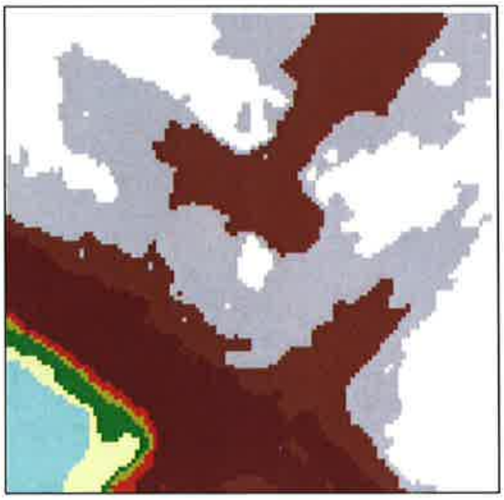


Figure 19. IDW raster

Point Raster vs. Terrain Raster

The Terrain raster was subtracted from the Point raster to see how much it differed from "actual" values. The differences were as much as 0.43 m. The RMSE (Root Mean Square Error) was computed (using all the sample points) to evaluate how much the predicted values differed from the actual. The RMSE was found to be 0.033608236. There were 438 out of 6790 (6.45%) comparison points that had differences greater than 5 cm from actual values.

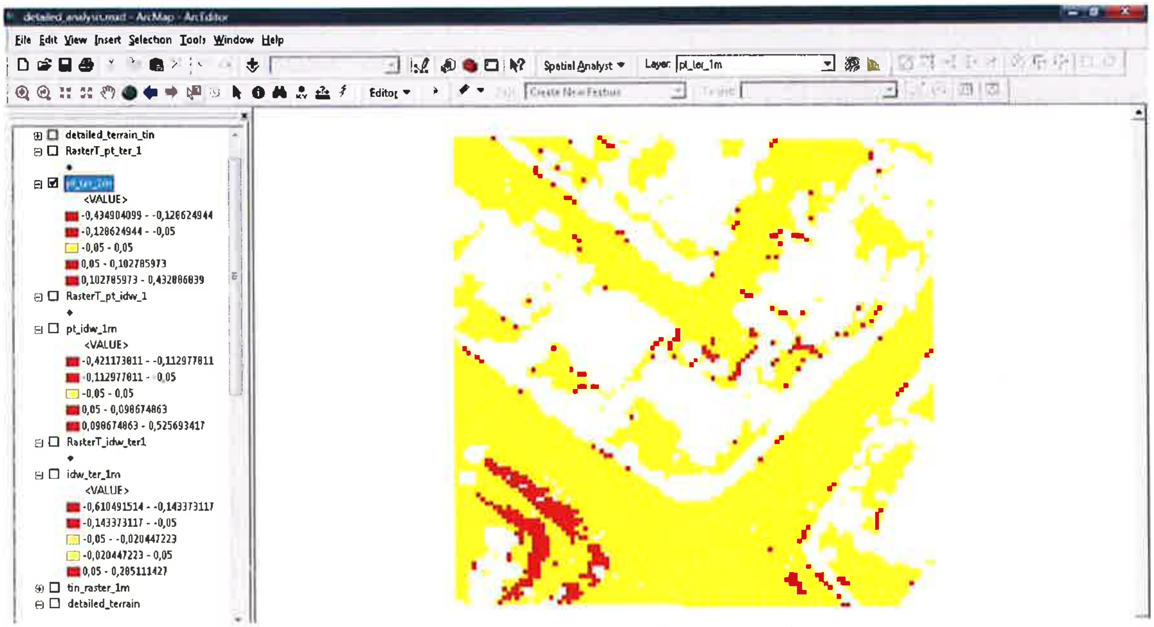


Figure 20. **Terrain raster subtracted from Point raster**

Point Raster vs. IDW Raster

The IDW raster differed from the Point raster by -0.42 to 0.53 m and the RMSE was 0.033242873, which was just slightly better than for the Terrain raster. There were 418 out of 6952 (6.01%) comparison points that had differences greater than 5 cm from actual values. Thus, it can be said that there were slightly more unacceptable areas for the Terrain raster than for the IDW raster.

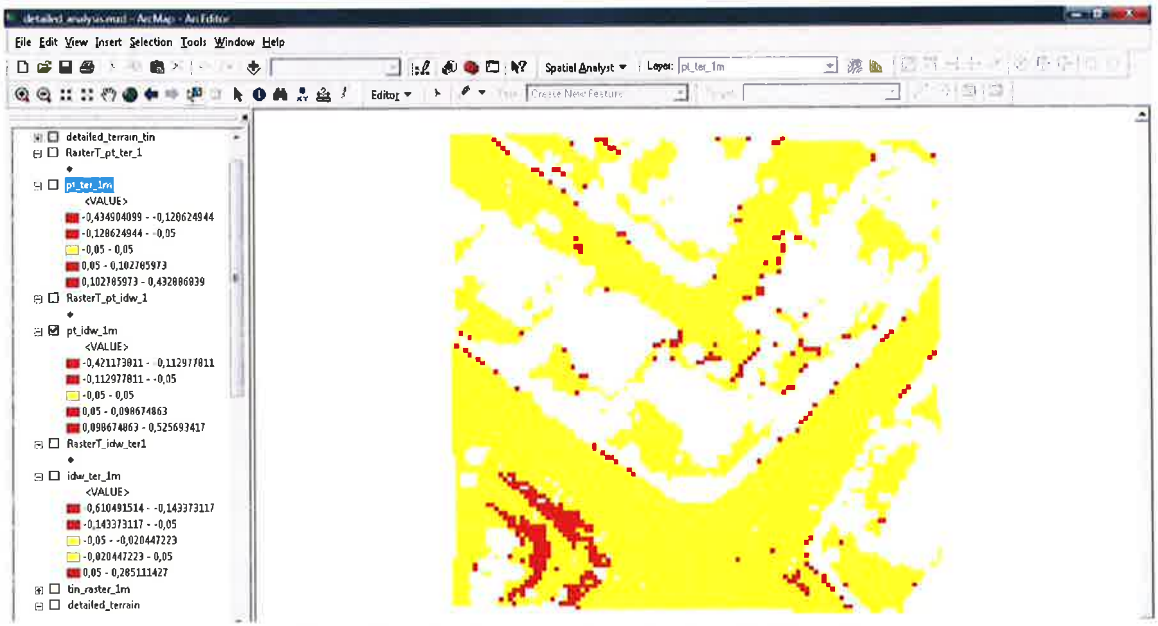


Figure 21. **IDW raster subtracted from Point raster**

IDW Raster vs. Terrain Raster

Comparing the IDW and Terrain rasters, it was found that the two rasters differed by -0.61 to 0.29 m and that the majority of the “unacceptable differences” occurred in areas without point elevation information.

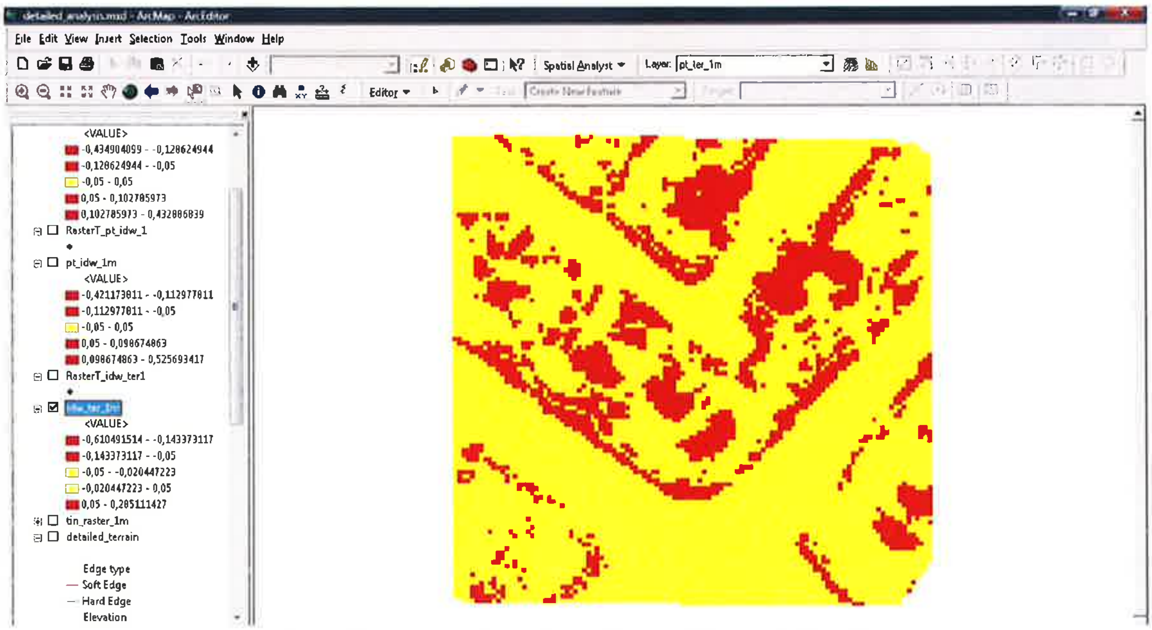


Figure 22. Terrain raster subtracted from IDW raster

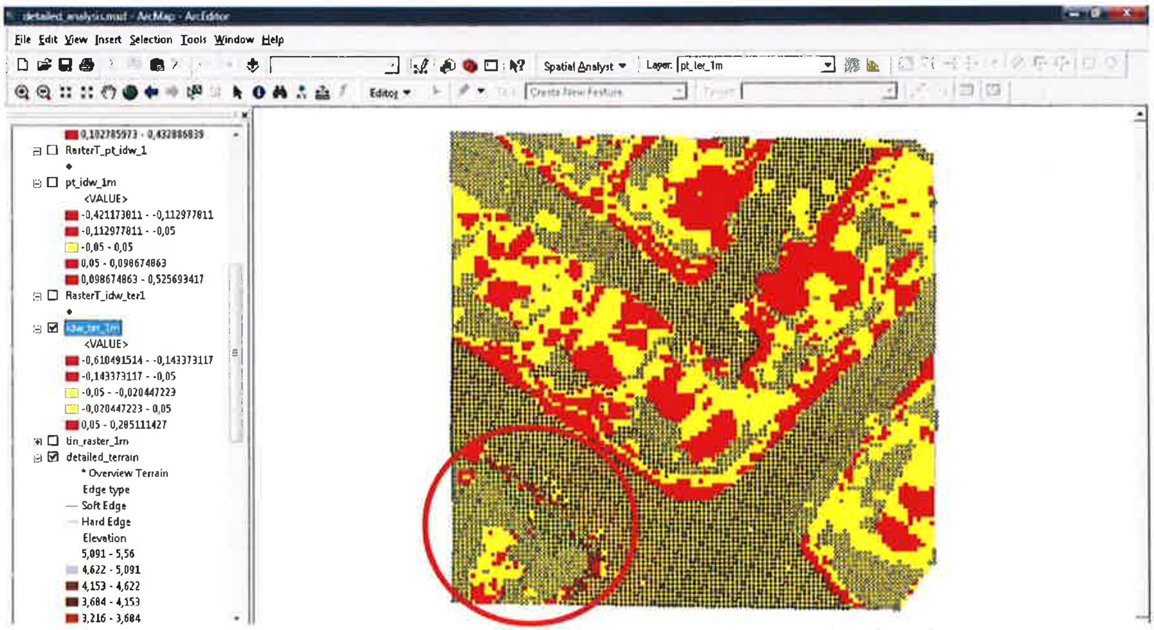


Figure 23. The red areas are mostly in regions without point elevations.

Examining the area (lower left corner of Figure 23.) where significant differences between the two rasters were observed despite the relatively high density of points, 67 grid points were identified for which point elevations and values for the terrain and IDW rasters were compared with each other in detail.

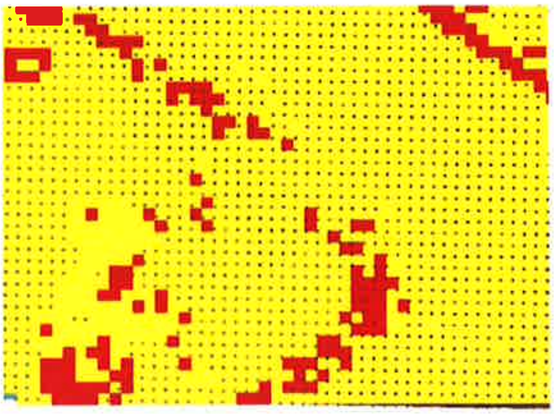


Figure 24. **Closer view of areas with big differences between Terrain and IDW rasters where point elevations exist**

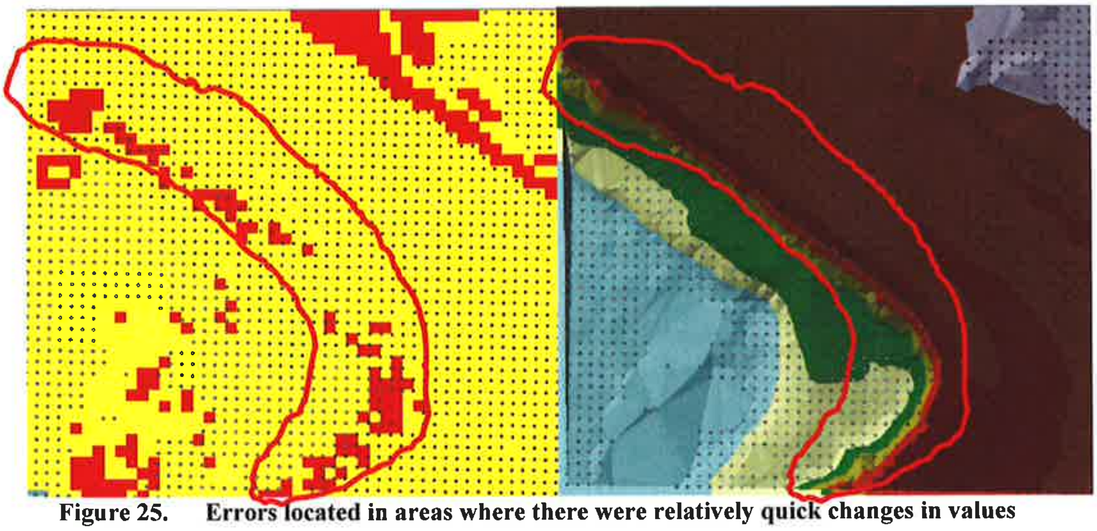


Figure 25. **Errors located in areas where there were relatively quick changes in values**

To determine which raster was more accurate in the "red areas," the differences between the Terrain and IDW rasters and the Point raster were computed. It was found that the range of differences between the Point and Terrain rasters (0.000071-0.418) was smaller than for the Point and IDW rasters (0.00097-0.696). For this sample of grid points, at the point with the biggest difference between Terrain and IDW rasters, the Terrain raster gave a more accurate value than the IDW raster (as compared to the Point raster). However, 60% of the time (for this sampling of points), the IDW raster gave more accurate values compared to the Terrain raster. Thus, the Terrain raster gives more points that deviate from the actual data but for a lesser range/magnitude. It must be noted, however, that the Terrain surface (NOT the Terrain raster) was found to be more accurate than the IDW raster for 75% of the red area points. Therefore, the Terrain method gives a surface that is more accurate than the IDW method, but the conversion of the Terrain surface to a raster introduces errors that significantly lower the accuracy of the resulting Terrain raster.

Comparing the IDW and Terrain methods for generating grids, the main differences between the two that may explain the slightly better accuracy of the IDW method are:

- The IDW method involves only one interpolation step, while the Terrain method involves two.
- More points can be used for predicting unknown values for the IDW method. If points are available at regular intervals (in both directions), the IDW can take information from

the four corners (if specified) but the TIN used for the Terrain method only gets information from 3 points.

- Even if only 3 points are specified for predicting the unknown value for the IDW method, the 3 points selected may differ from those used for the Terrain method because the Terrain method uses a criterion than prevents building/generation triangle surfaces that overlap. To illustrate, in Figure 28. if the unknown cell center is located as indicated by the red dot, the Terrain method will use point values from Pts. 1, 2 and 3. For the IDW method, however, Pts 2, 3 and 4 may be used for the estimation if it were specified that only 3 points shall be considered.

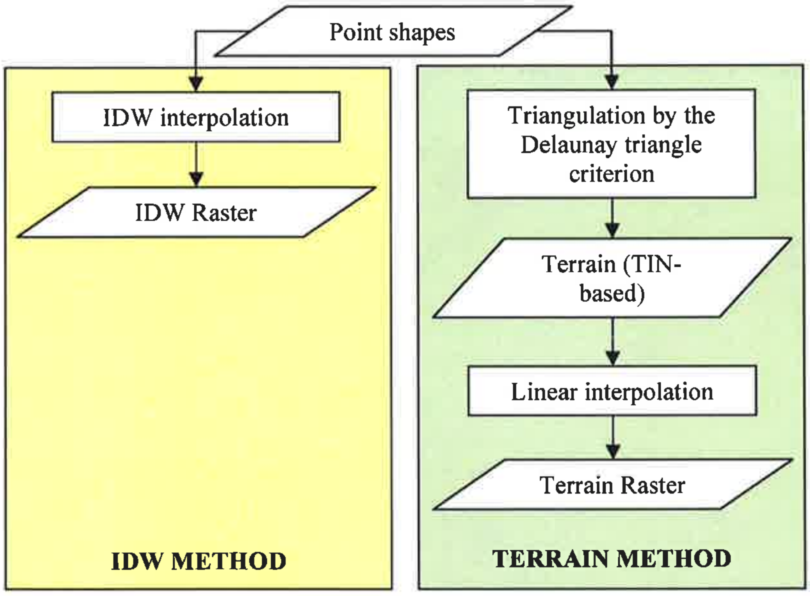


Figure 26. Comparison of processes for IDW and Terrain methods

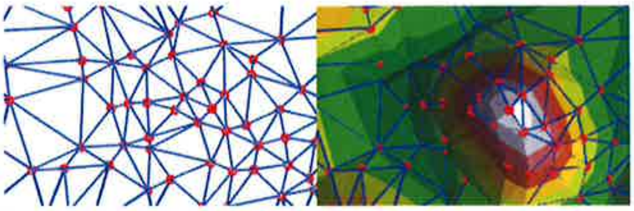


Figure 27. Triangulation for creating the TIN surface

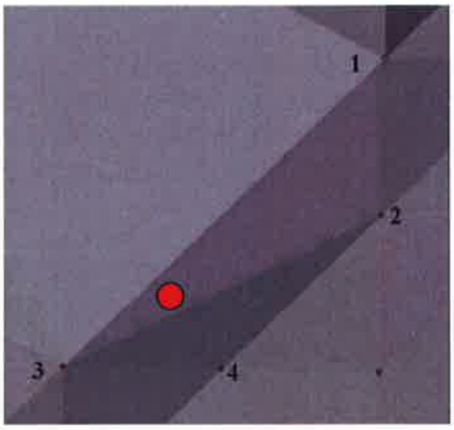


Figure 28. Points used for prediction of unknown value

5. FLOOD MODELLING OF MIXED URBAN AREAS IN GREVE, DK

This chapter describes the different models that have been built and used for the project.

5.1. Detailed Lower Olsbaekken MOUSE-Mike SHE Model

Olsbaekken has a high percentage of green areas, especially in the upper part of the catchment, where water can infiltrate into the ground or be removed from the soil through evapotranspiration. The groundwater table is also shallow occurring at depths of 1 to 4 m in the lower part of the catchment near the coast. Thus, all the major hydrological processes should be included in the MMSHE model.

The hydraulic network model used was an existing MOUSE model of the stormwater drainage system for the Olsbaekken catchment.

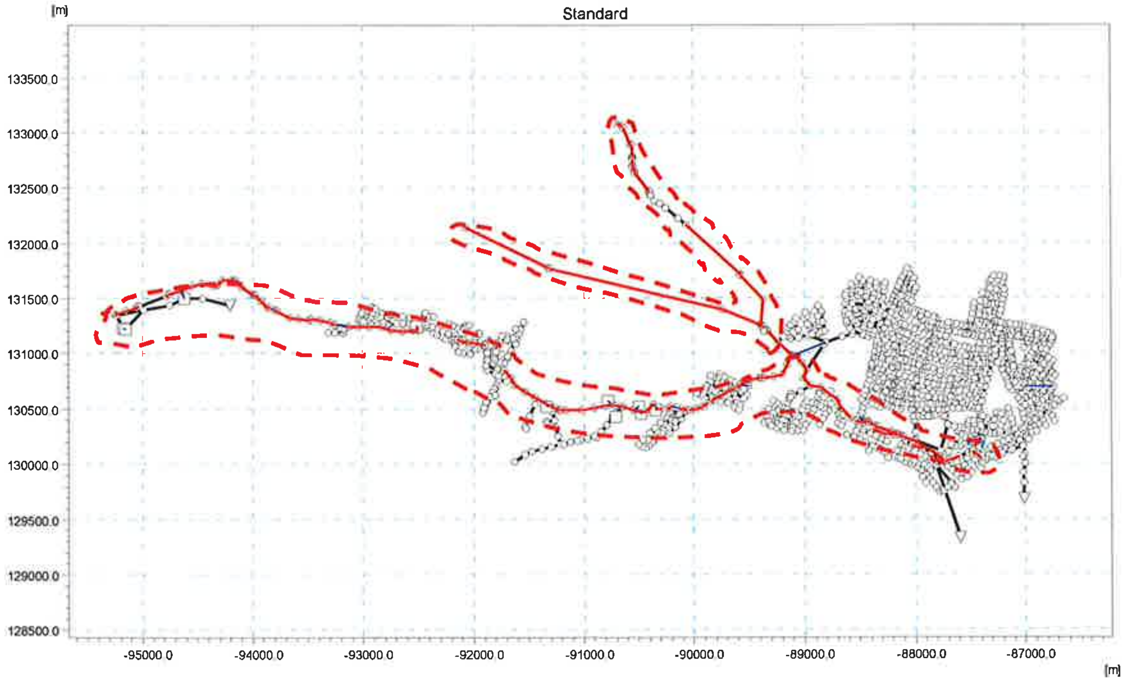


Figure 29. Olsbaekken MOUSE model showing locations of streams

It drains 1634 catchments comprising about 24 square kilometres of area where around 5 square kilometres is impervious and contributes to runoff. The network is horizontally longitudinal running from the west to the east towards the outlet to the sea. It is a very detailed network model having 1789 nodes, most of which are located in the downstream part.

Other statistics about the model are:

- Basins = 23
- Outlets = 3
- Weirs = 35
- Pumps = 3

Most of the links are circular pipes but 3 streams that merge downstream and flow out to sea are included in the MOUSE model and represented by open channels.

The full MOUSE model was used in the detailed MMSHE model even if the domain covered only the downstream part of the study area. The MOUSE model was not cut for the detailed lower Olsbaekken MMSHE model in order to try to keep the integrity of the given MOUSE model and ensure that the conditions in the drainage system are more or less consistent even if only a section of it is being analyzed. However, this means that for the detailed model, nodes that are not linked to Mike SHE use virtual basins to "store" water that comes out of the manholes. Since flood depths over linked nodes downstream will be different due to the coupling with the overland model, the hydraulics will be altered. Thus, when disregarding part of a MOUSE model for coupling, it should be ensured that no flooding occurs in the "discarded" nodes that are connected to nodes downstream that have been linked to the overland flow model.

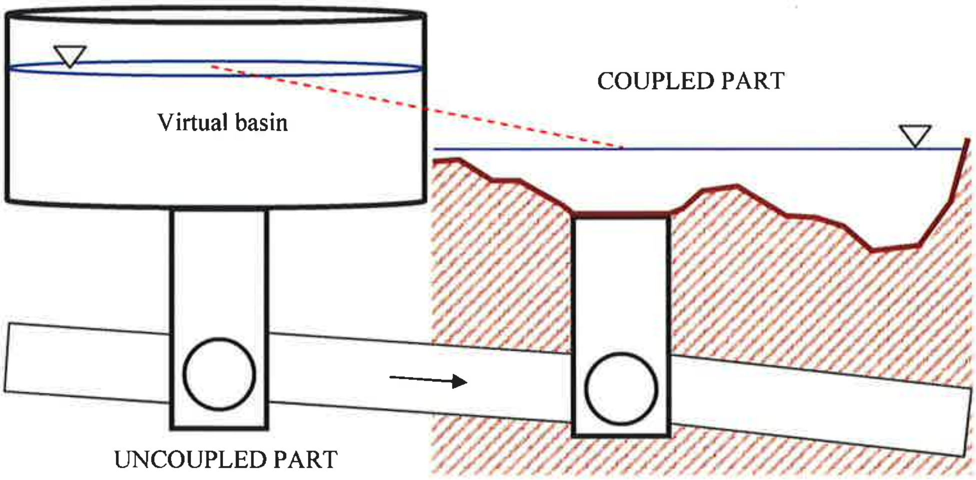


Figure 30. **Illustration of "discontinuity" when one part of a network model is coupled and connected parts uncoupled**

The components of the Mike SHE model for lower Olsbaekken are described in the following sections:

a) Water Movement Modules

Almost all Water Movement modules in Mike SHE (OL, UZ, ET, and SZ) were utilized in the model. The Finite Difference computational scheme which uses the diffusive wave approximation of the Saint Venant Equations was selected for the Overland Flow module. Antecedent soil moisture conditions are believed to significantly influence flooding in the study area, and so a relatively detailed view of the unsaturated zone showing actual evapotranspiration, infiltration, and recharge to the groundwater is desired. Nevertheless, a full view of the dynamics in the zone is not required. Thus, for this study, the Gravity Flow option was selected for the UZ module—less complex than the full Richards Equation and yet more accurate and descriptive than the 2-Layer Water Balance Method. The big percentage of green areas in Greve also necessitated the inclusion of the ET module, and since the groundwater table is shallow and is expected to interact with the drainage network and natural channels in the study area, the Saturated Zone module was included.

b) Model Domain and Grid

The extent of the model was delineated based on the coverage of the MOUSE model and the delineated urban catchments. The subcatchments that contain the relevant nodes were selected and comprised the model domain. A grid size of 5 m was specified for the model which is fine enough to adequately represent the terrain and yet still within software limitations.

Figure 31. Model domain identified from urban subcatchments and the MOUSE model

c) Topography

For this particular model structures were added to the DTM but their correct heights were not used. Instead the buildings were assigned a uniform height of 30 m, which is acceptable as the rainfall is not applied in a distributed way over the built-up area and the resulting topography can still show the flow around the buildings.

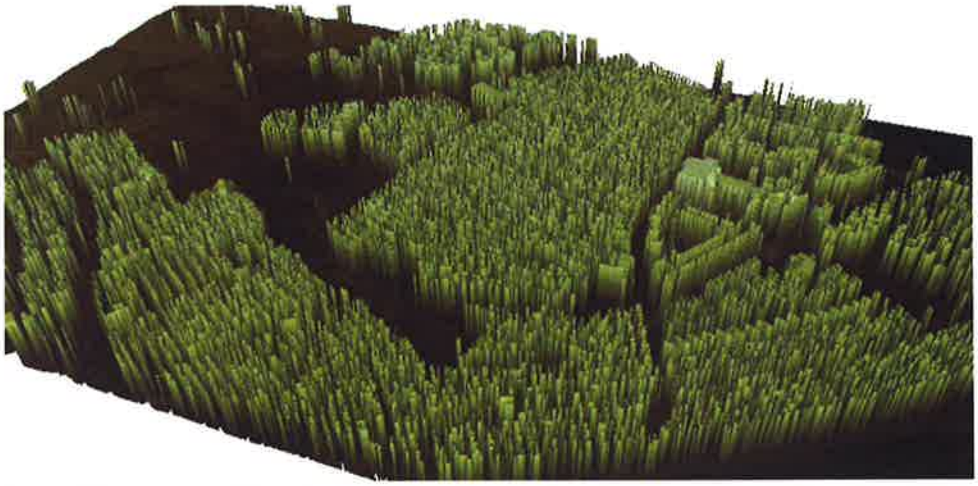
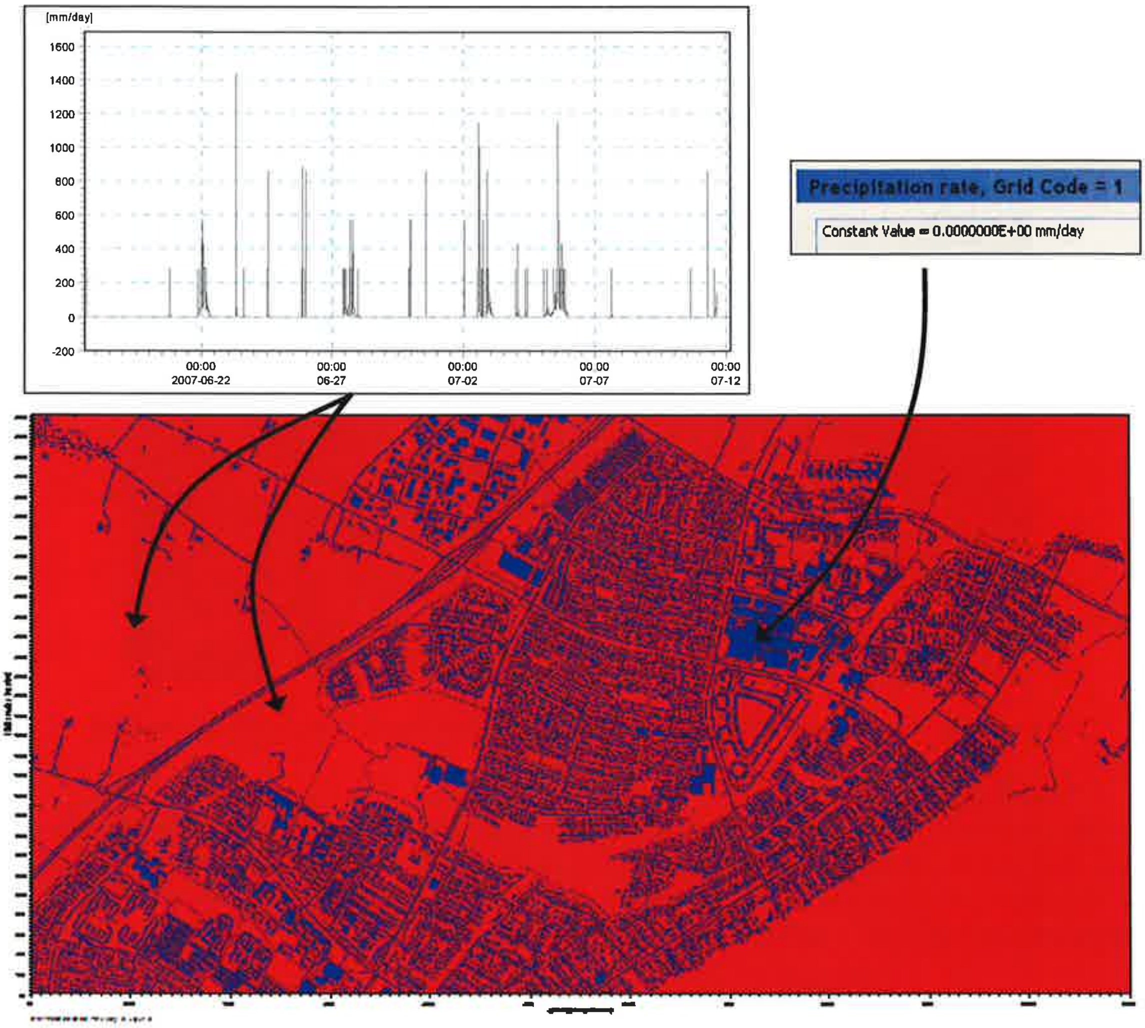


Figure 32. Lower Olsbaekken topography showing structures assigned heights of 30 m

d) Meteorological Conditions

The model area was divided according to whether rainfall falling on the surface went into Mike SHE or into MOUSE. It was assumed that rain falling on paved areas (parking lots, buildings, big and small roads) is first collected by the drainage system and so precipitation over paved areas was excluded from Mike SHE because they have already been considered in the MOUSE model as the "runoff-contributing areas".



Precipitation rate, Grid Code = 1

Constant Value = 0.0000000E+00 mm/day

Figure 33. Precipitation distribution for Lower Olsbaekken. Red areas retained and blue areas excluded (to MOUSE) in Mike SHE

Evapotranspiration was assumed to be a significant process which must be considered in the model because of the high percentage of green/unpaved areas in the study area. It was treated the same was as precipitation and evapotranspiration over paved areas was disregarded since it was considered to be significant only in green areas.

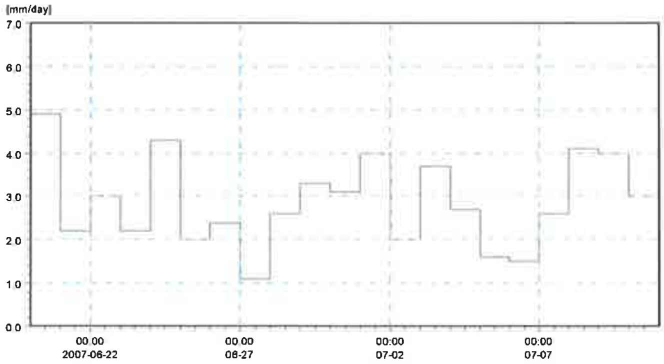


Figure 34. Potential evapotranspiration over the study area

e) Land Use Characteristics

The distribution of different types of vegetation around the study area was described by specifying a Mike grid file. Five (5) types of vegetation were specified:

- Code 1: Graes (Grass)
- Code 2: Vaarafgr. (Spring crop)
- Code 3: Vinterafgr. (Winter crop)
- Code 4: Hav (Sea)
- Code 5: Graes brak (Unused field)

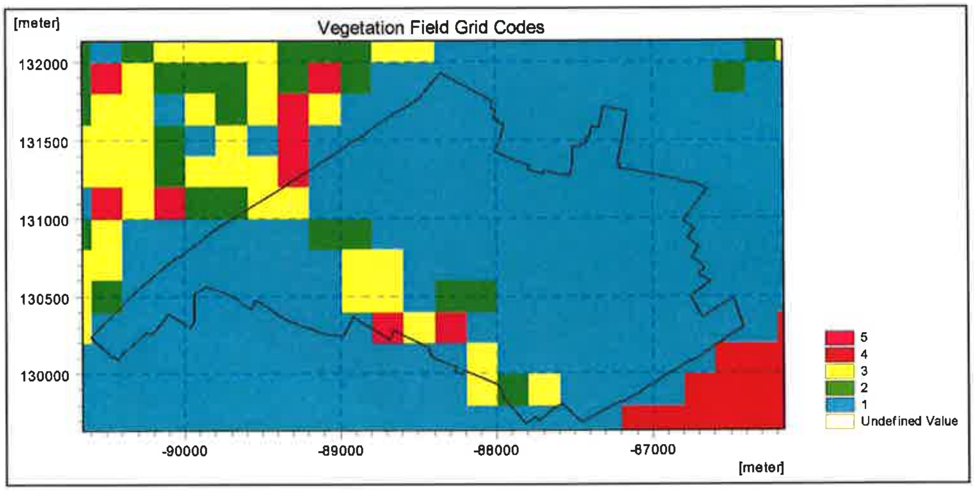


Figure 35. Vegetation grid codes in the study area

It can be observed that the Vegetation grid covers the paved areas as well, but this will not matter in the model since potential evapotranspiration has been neglected over the paved areas.

f) Overland Flow Conditions

Initial values for surface flow resistance (Manning M) were:

- Paved areas (big and small roads, parking lots): M = 32
- For the rest: M = 5

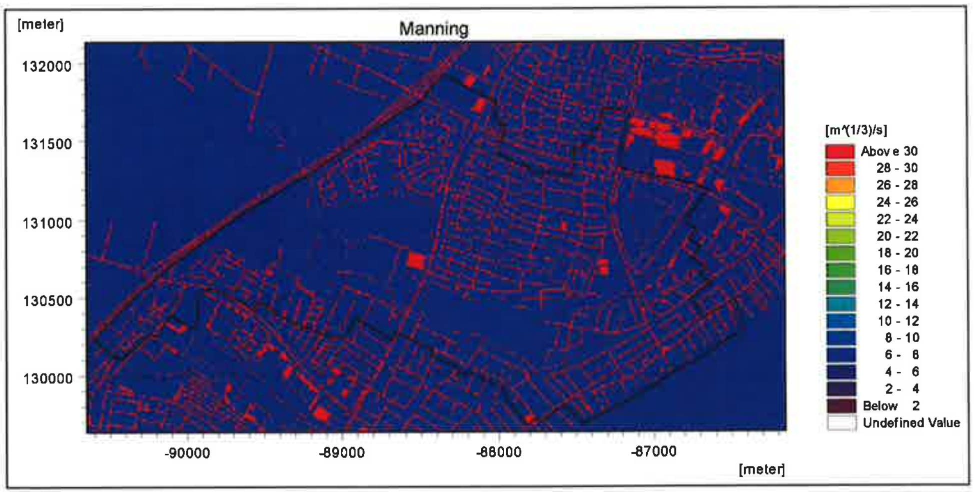


Figure 36. Distributed overland flow resistance values given by Manning M

This indicates a greater resistance to flow over green areas compared to paved areas, which is a reasonable assumption.

g) Unsaturated Flow Conditions

The Gravity Flow option was selected for the unsaturated flow module in this model. It still accurately describes the process but does not go into details about the dynamics in the unsaturated zone as is the case with the full Richards equation. Automatic Classification of the UZ was selected and groundwater elevations were also specified under this option.

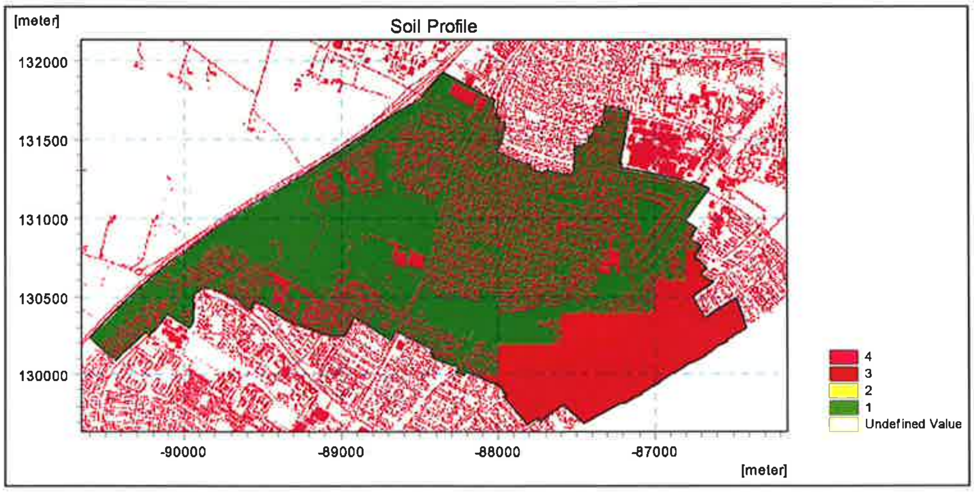


Figure 37. Soil profile distribution in lower Olsbaekken

3 general soil types were specified in the model:

- Code 1 (Till clay): 32 meters of clay
- Code 3 (Fine sand): 32 meters of a combination of sand and clay
- Code 4 (Built-up area): 140 meters of clay

h) Saturated Flow/Groundwater Conditions

The different geologic layers and lenses were described in the model. For each layer, geologic parameters such as hydraulic conductivity, specific yield, and specified storage were specified. Information about groundwater pumping was also given in the model.

Subsurface Drainage was also included in the model since buildings, houses and sports fields in the study area were assumed to have underground drains.

i) Saturated Zone Drainage

In the model, SZ drainage was described as distributed according to drainage options such that the grid cells were categorized and given appropriate codes depending on how and where they drain into.

- *Option Distribution.* For this model, a value of 4 was assigned to drained areas (buildings and sports fields) and 2 for the rest of the domain. Giving a value of 2 does not mean that these areas are also made to drain into the MOUSE model. This is because in the subsequent section, the Drain Codes for these areas were set to zero, which means that they will not produce nor receive any drain flow.

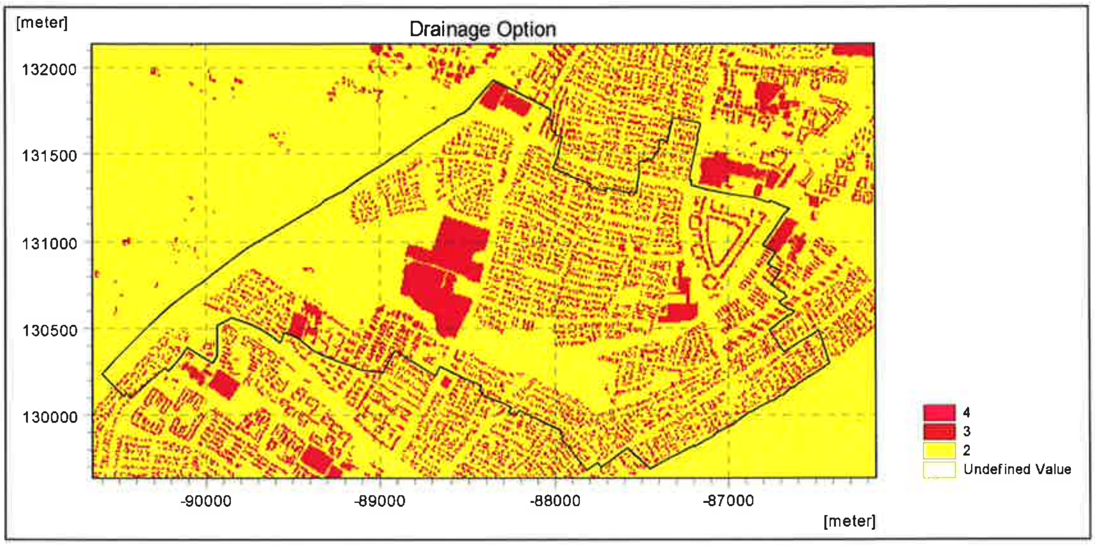


Figure 38. Drainage option distribution for lower Olsbaekken

- *Drain Codes.* The drained areas in the detailed Olsbaekken model was subdivided into 25 grid codes (11-35). Even the cells outside the model domain were assigned a drainage code and a drainage manhole (one of the drainage manholes within the domain) because all cells assigned an option distribution value must have a corresponding drain code. Assigning a drain code for cells outside the domain will not affect the saturated zone since computations are not performed for areas outside the domain.

- *Time Constant.* Different time constants were specified for buildings and sports fields. Typical drainage rates of 1e-5 for houses and 2e-7 for sports fields were specified in the model.

- *Level.* For this model, different drain levels were assigned for sports fields and buildings. Based on Swedish standards, it was assumed that buildings had drains 2 m below them and sports fields, 1 m. However, since drain levels are referred to the ground elevation in the topography, the heights of the buildings were considered such that a drain level for a particular building was its height plus 2 meters below the ground.

  For this model, the buildings were given a uniform height of 30 m, thus it was relatively easy to determine the drain levels. Instead of -2 m, the value for areas covered by buildings was given as -32 m, and drain levels for sports fields was given as -1 m.

j) Extra Parameters

The appropriate PFS file referring to the coupled MOUSE model and containing the different drainage manholes for each of the 25 codes was specified in the "Extra Parameters" section of the model.

The PFS and ADP files required for properly coupling the Mike SHE and MOUSE models were built according to the procedures outlined in Section 2.2.3. (Coupling the MOUSE and Mike SHE Models).

The PFS file referred to the MOUSE model of Olsbaekken and identified 25 drainage manholes in the study area. The ADP file specified in the MOUSE model contained the list of nodes and links that should be coupled with the Mike SHE model.

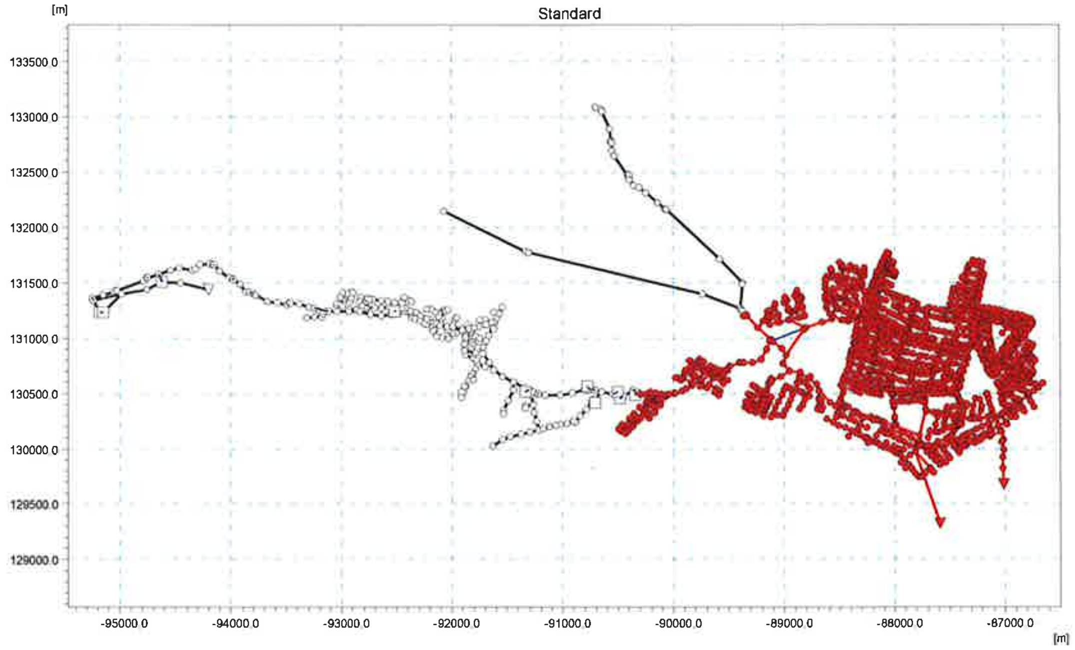


Figure 39. Coupled nodes and links for detailed lower Olsbaekken MMSHE model

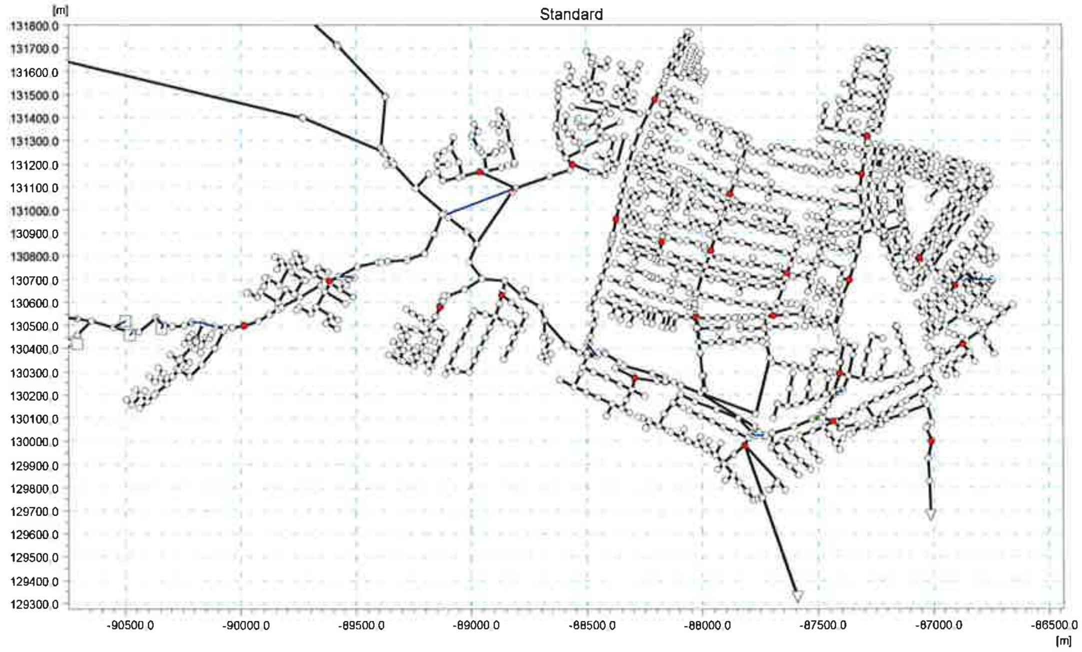


Figure 40. SZ drainage manholes from among linked nodes in lower Olsbaekken MMSHE model

5.2. Overall Olsbaekken MOUSE-Mike SHE Model

An MMSHE model of the whole Olsbaekken catchment was built in order to get a picture of overall hydrologic conditions especially during the July 2007 flood event. In the detailed model, the runoff from the upper catchment was computed solely with the MOUSE Runoff Model according to the specified percentages of impervious areas. However, given the big percentage of green areas and high groundwater levels, interaction of runoff and infiltration over pervious areas with the drainage system and the downstream catchments is expected, and thus, more accurate overland flows and soil moisture conditions are expected with the overall model.

The flood event of 5th July 2007 is being attributed to excessive runoff from the upstream catchments where the ground had become saturated due to continuous rains. Thus, the main purpose of building the overall model is to confirm the hydrological processes that caused the flooding and determine the volume of water from the green areas upstream that flowed downstream.

A 25-m grid was selected for the model, which is less refined than the detailed model for lower Olsbaekken. The bigger grid size is not expected to accurately show the features on the land surface such as roads or buildings. However, the main interest in using the overall model is to analyze the water balance in the catchment and so the use of bigger grids would still be suitable as long as the total extent of pervious and impervious areas, when translated into grids, remain consistent.

Building the model involved essentially the same procedures followed for the detailed model and in Section 2.3. The same MOUSE model as the one used for lower Olsbaekken was used, but this time all the nodes and links were included in the coupling. For the overall Mike SHE model, most of the components of its various modules used the same grid, time series, and database files as the detailed model. This is because the two model areas are adjacent to each other and are covered by the same grid file for items such as land use, soil distribution, geologic layers, and initial groundwater head. Major differences from the detailed model are explained in the following sections:

a) Model Domain

Similar to the detailed model for the lower catchment, the extent of the overall model was based on the MOUSE model and subcatchment divisions. However, urban sub-catchments have not been identified for the upper part of the catchment. The watershed limits may be inferred from an existing Mike 11 network file which shows the various streams running through the area. But for a more accurate delineation, the Hydrology tool in ArcGIS was used in order to identify the sub-catchments from the available DTM.

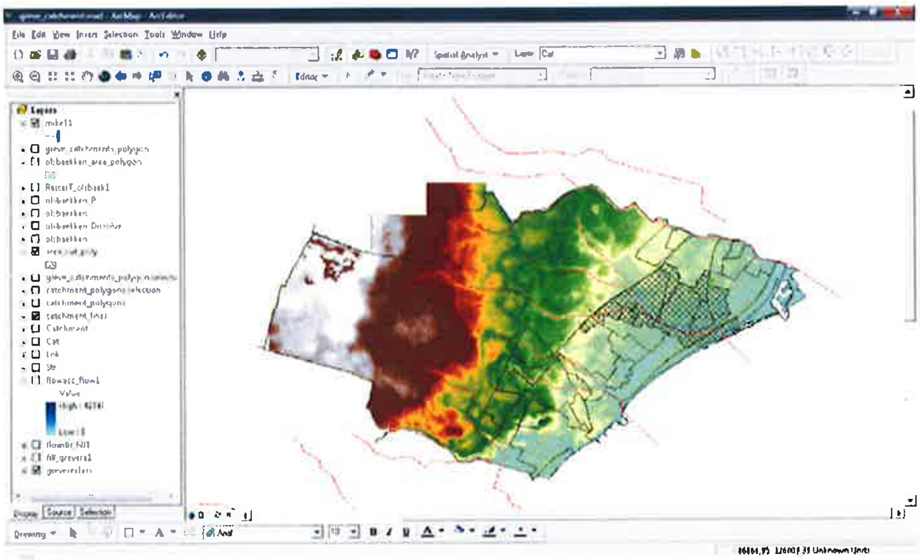


Figure 41. **DTM of Olsbaekken showing Mike 11 network (red lines), urban subcatchments (black outline), and the domain of detailed Olsbaekken model (hatched)**

Flow paths and accumulation points were identified based on the terrain. Rivers and streams could be defined, and subcatchments for specified river reaches could be delineated.

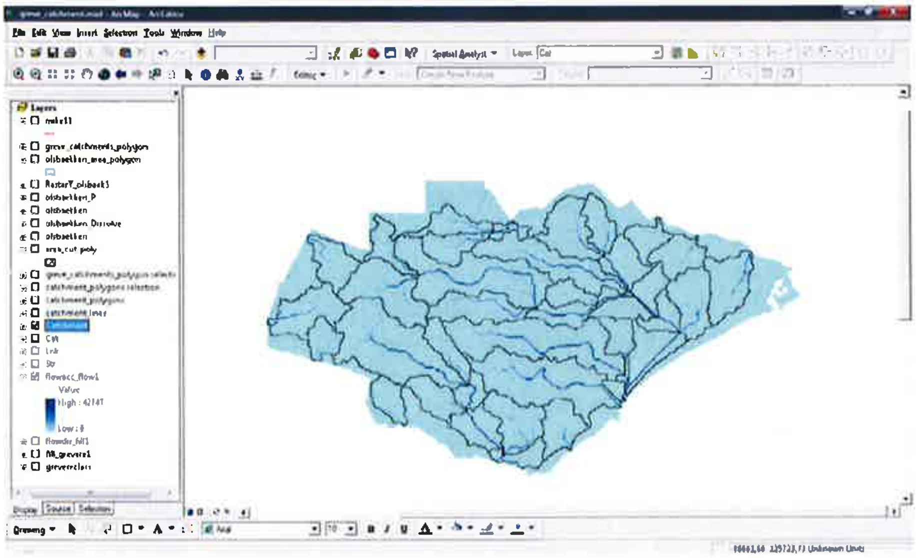


Figure 42. Subcatchments identified based on identified water bodies using Hydrology tool in ArcGIS

The domain for the overall model comprised of the sub-catchments containing all the nodes of the given MOUSE model. The catchments connected to MOUSE nodes have been also identified according to the topography and so identifying the model extents through delineated sub-catchments is reasonable.

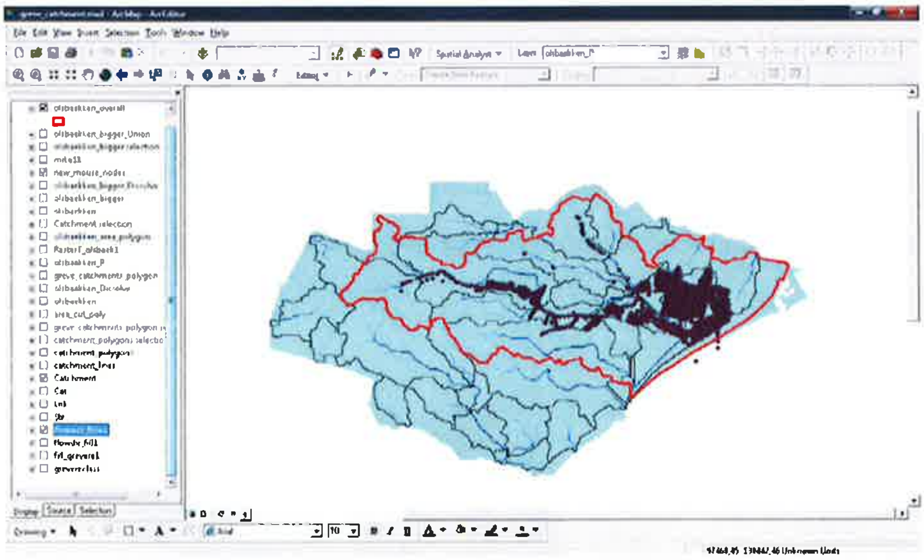


Figure 43. Overall Olsbaekken model domain identified from MOUSE and delineated subcatchments

The identified domain for the overall model had an area of about 31 square kilometres (30690847 sq. m.) with dimensions of 12 km x 5 km. It covered the whole MOUSE model for Olsbaekken and contained 4 major streams, 3 of which were reflected in the MOUSE model.

b) Topography

The DTM for the overall model was much coarser than the one for the detailed model because of the bigger grid size (lower resolution). The overland structures were still included in the DTM but since the grid size was bigger than the smallest dimension of some of the structures, there were inaccuracies with respect to the locations and connectivity of the structures.

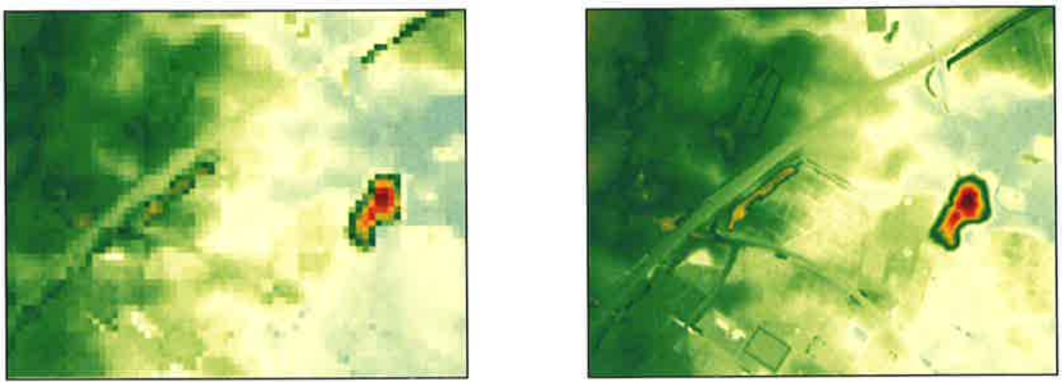

(a) 25-m grid size DTM (b) 5-m grid size DTM

Figure 44. **Poorer representation of surface features for coarser DTM**

c) Meteorological Conditions

Similar to the detailed model, built-up areas (big and small roads, parking lots, and buildings) were excluded from the Mike SHE model by specifying zero precipitation over them. Since the overall Mike SHE model uses a grid size of 25 m, it is expected that the structures in the study area will not be accurately represented, at least in terms of location. However, although the coverage of the grid file developed from shapefiles is not accurate, the translation maintains the total area of the shapes. For this model, the grid file for the built-up areas (buildings, roads, and parking lots) covers a total area of 4.3 sq. km. Comparing with the catchments in the MOUSE model, it was found that the runoff-contributing area is 4.6 sq. km., which means that the built-up areas specified in the Mike SHE model corresponds well with the runoff areas in MOUSE with only about 8% of difference between the two. This means that water balance in the model is maintained since the excluded "climate" areas in Mike SHE correspond well to the runoff catchments in MOUSE.

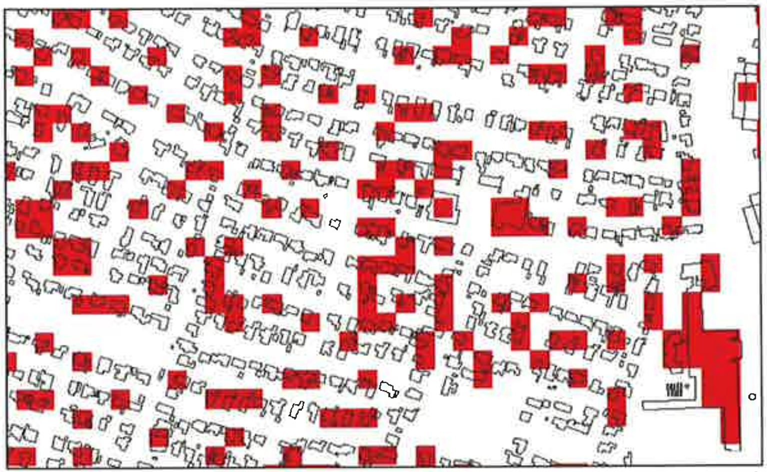


Figure 45. **Inaccuracy in converting building shapefiles (black outline) to grid of relatively low resolution (red shapes)**

d) Extra Parameters

The appropriate PFS file referring to the coupled MOUSE model was specified in the "Extra Parameters" section of the Mike SHE model.

The PFS and ADP files required for properly coupling the Mike SHE and MOUSE models were built according to the procedures outlined in Section 2.2.3. (Coupling the MOUSE and Mike SHE Models). The PFS file referred to the same MOUSE model of Olsbaekken that was used for the detailed lower Olsbaekken model. This time, only 22 drainage manholes were identified because sub-catchment divisions for the overall model were coarser.

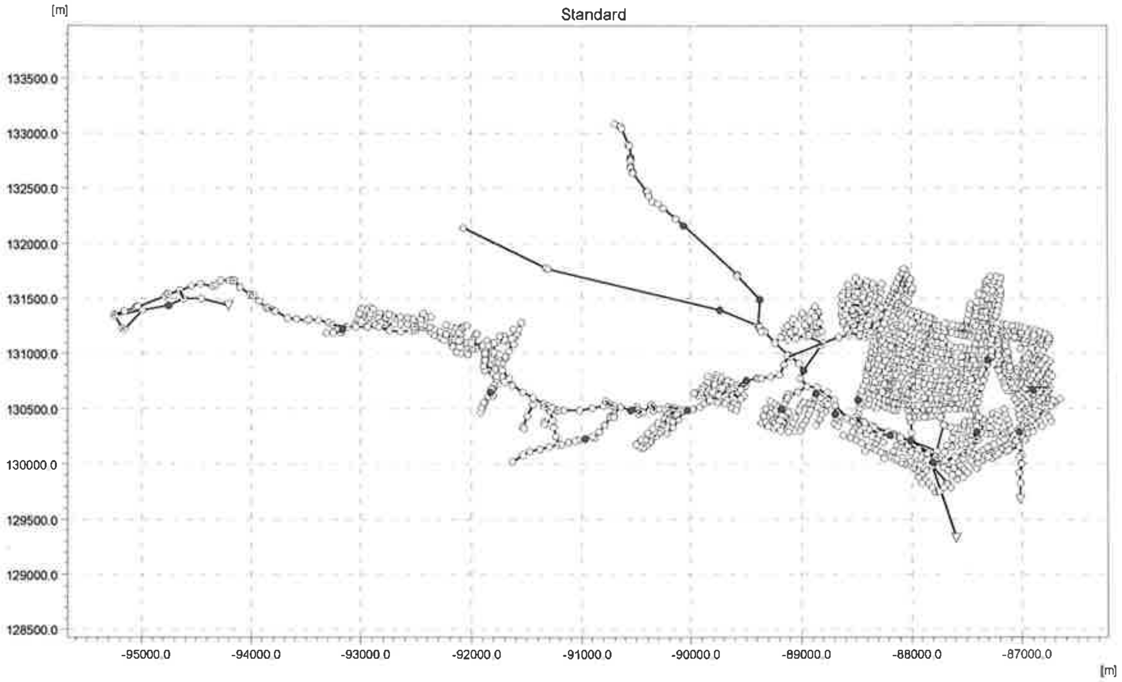


Figure 46. SZ drainage manholes for overall Olsbaekken MMSHE model

The ADP file specified in MOUSE telling it that it is coupled to Mike SHE was bigger than that for the detailed model because it included all the nodes and links of the Olsbaekken MOUSE model for coupling.

5.3. Greve Midt Mike Flood and MOUSE-Mike SHE Models

The center of Greve (Greve Midt) has a Mike Flood model that is able to produce accurate urban flood maps based on overland flows described in the 2D Mike 21 model as its exchanges flows with the linked 1D MOUSE pipe flow model. The well-described terrain which reflects overland structures allows water expelled from the overwhelmed pipe network to realistically move over the land surface following channels and roads and flowing around buildings. However, the Mike Flood model does not consider other important hydrological processes such as infiltration and flow exchange with groundwater which, for this case, are considered to be significant because of the land surface characteristics of the area. Mike SHE, a 2D model that is able to describe all the land-phase hydrological processes, may be more appropriate for building the flood model instead of Mike 21.

To evaluate the suitability of a MOUSE-Mike SHE model for producing accurate urban flood maps, an MMSHE model was built and its results compared to those of the existing Mike Flood (MM21) model of the area.

5.3.1. Existing Mike Flood (Mouse-Mike 21) Model

The existing Mike Flood model of Greve Midt is made up of coupled MOUSE and Mike 21 models. 915 of the 1211 nodes of the network are each linked to a grid cell in the overland flow model through Urban Hydrodynamic link types. The urban link is designed to describe the interaction of water when a manhole is overtopped or when overland flow enters a drainage network.

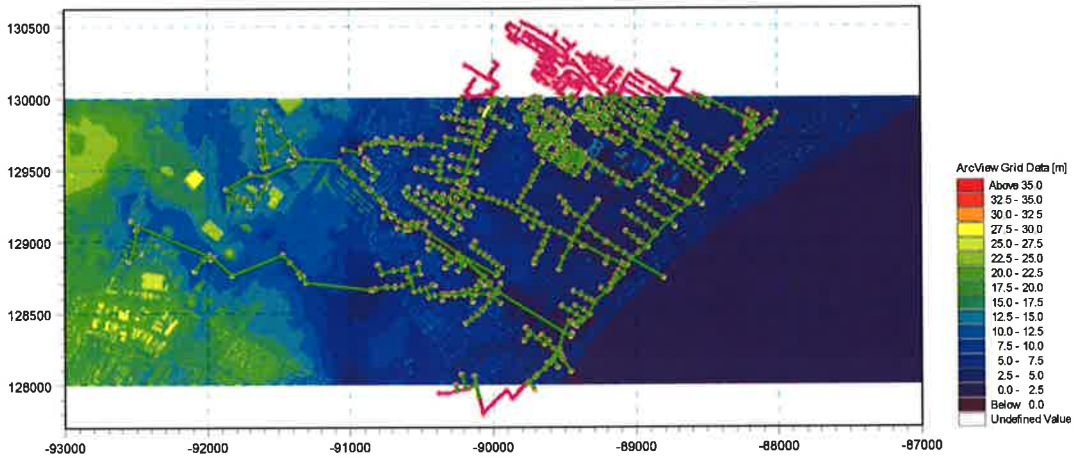


Figure 47. Greve Midt Mike Flood model showing the MOUSE network

The model assumes that only rainfall over impervious areas contribute to pipe and overland flow in the study area. Runoff from impervious areas is collected by the drainage network, and when the system is overwhelmed, the excess water flows out onto the surface through unsealed manholes and flows overland following the topography or goes back into the drainage system depending on the flow conditions on the surface and in the pipe system.

The drainage network is represented by a MOUSE model composed of the following elements:

- Manholes = 1195
- Basins = 14
- Outlets = 2
- Weirs = 16
- Pumps = 2

It has a relatively dense network especially in the north-eastern part of the domain, which is also the location of the city center. It has a total catchment area of about 5.6 square kilometres, 2.6 sq. km. (~50%) of which contribute to runoff. Two streams in the area are represented by closed and open channels in the model.

The Mike 21 hydrodynamic flow model has a bathymetry file representing the topography of the study area with a grid size of 2.5 m. It was closed-in by assigning land values (30 m) for the boundary cells, which means that water occurring within the model area stays inside flowing overland or through the drainage system. A uniform Manning M of 32 was also assigned to the terrain, a reasonable estimate since M=100 is for smooth surfaces and M=10 is for thickly vegetated areas. Structures such as roads and buildings are reflected in the topography grid in order to accurately simulate flows around structures during flooding. However, in addition, the correct heights for the buildings are also shown in the topography.

Figure 48. Topography grid for Mike Flood model showing correct building heights

No precipitation is applied to the Mike 21 model, which means that it is assumed that rainfall over pervious areas infiltrate the ground and is taken out of the coupled system and will not contribute to pipe and overland flows.

5.3.1.1. Cutting the Mike Flood Model

The domain of the given Mike Flood model is quite extensive being 2401 x 801 grid cells (12 sq. km.) in size. If this model is to be properly compared to an MMSHE model, the two models should have the same extents. However, computational grid extent limitations for Mike SHE prevent the creation of a Mike SHE model that has more than 1000 grid cells in any direction and 250,000 computational cells. Thus, it is necessary that the Mike Flood model be cropped to a size that is practicable for a Mike SHE model for proper comparison of the two models later on.

The bathymetry for the new Mike Flood model was limited to a size of 600 x 400 grid cells (2.5 m grid size). This time, only 409 MOUSE nodes were linked to Mike 21 grids.

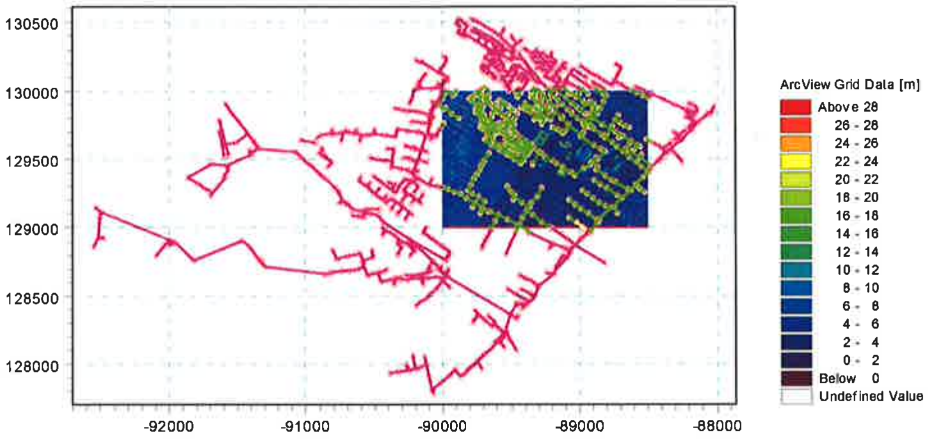


Figure 49. Resized Greve Midt Mike Flood model

Some factors must be considered before cutting the given working flood model. Aside from retaining the focus areas (where flooding is being analyzed), it should be ensured that cutting the model will not affect results such that the extents and magnitudes of flooding will remain the same as those produced with the complete model. This may be difficult to do since reducing the model essentially uncouples the 2 systems in the areas that are removed, which affects the hydraulics in the whole pipe system. This is because for "uncoupled" nodes, instead of excess water spilling out of the manholes and spreading out onto the topography, it is instead temporarily stored in virtual basins of a certain dimension (with a cross-sectional area 1000 times the area of the manhole and 10 m high) and the modified "flood levels" will change the hydrodynamics in the downstream links. In order to ensure that the behaviour of the system is not considerably changed by cutting it, the cut parts of the drainage system must be those that are never flooded or are not connected to the parts of the network being retained. A relatively quick and good way to check if the validity of the cut model is maintained is to compare the results before and after cutting as described in the following section.

5.3.1.2. Comparison of Original and Cut Mike Flood Models

In this study, in order to check whether cropping the given Mike Flood model would affect results, the original and cut models were run using the same rainfall boundary conditions and their results were compared. The rainfall time series during the flood event of 5 July 2007 was selected for the simulation which was run for the period 4 – 7 July 2007.

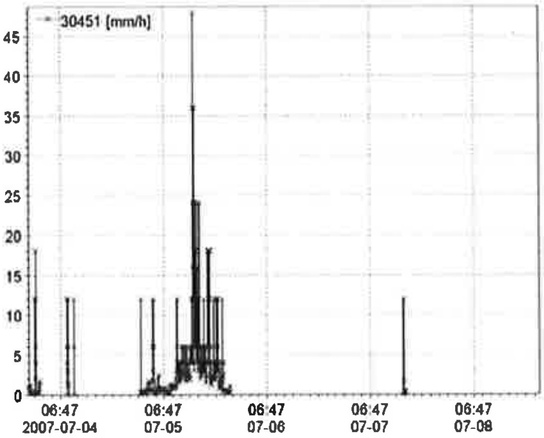


Figure 50. **Rainfall event used for the simulation (4-7 July 2007)**

For each model, the grid file showing the maximum depths reached during the simulation period was obtained and water depth time series were obtained at 2 points in the model. Also, for easier comparison, the results of the original Mike Flood model were cropped to the size of the cut model.

Extracted grid series:

- Maximum depth over the simulation period

Extracted water depth time series:

- Pond at the city center: (j,k) = (250,165)
- Space beside the gym: (j,k) = (305,245)

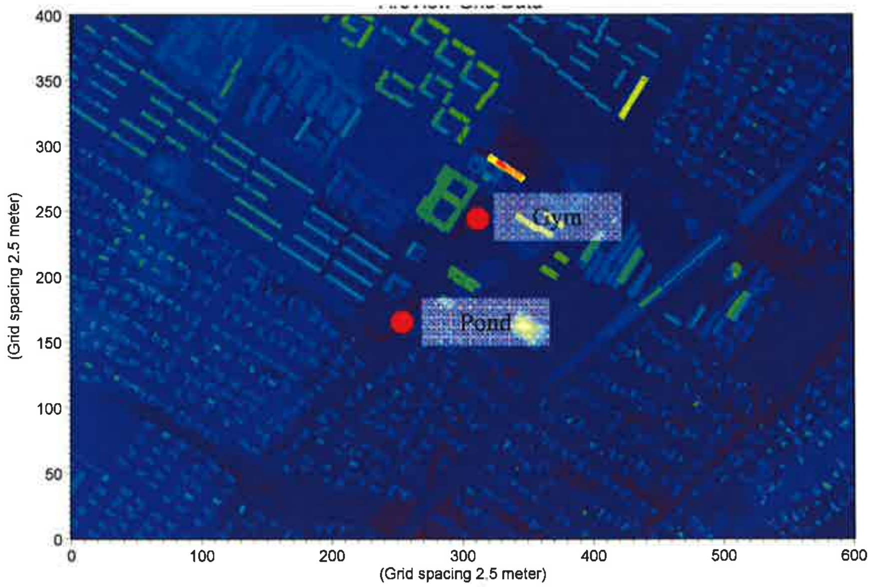


Figure 51. Locations of water level time series extraction points

The results showed that the cut model gave slightly different results from the original. Flooding was still observed in areas that were much flooded in the original model, and extracted water depth time series indicated that the variation of water depth at these places were very similar in both models. However, there were places that were flooded in the cut model that were not in the original.

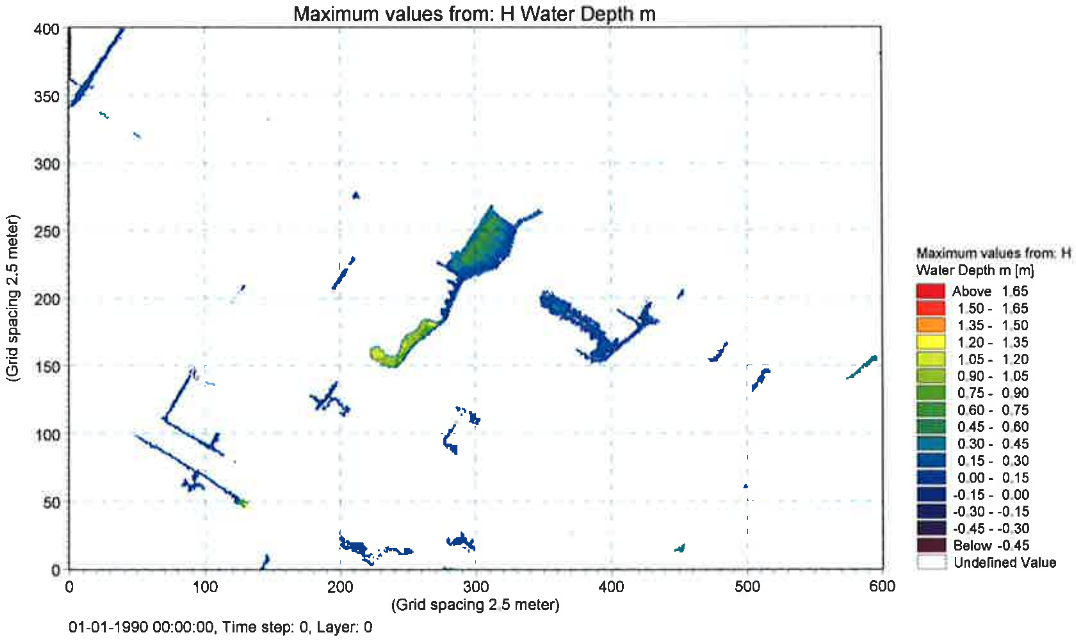


Figure 52. Maximum water depth over simulation period for original Mike Flood model

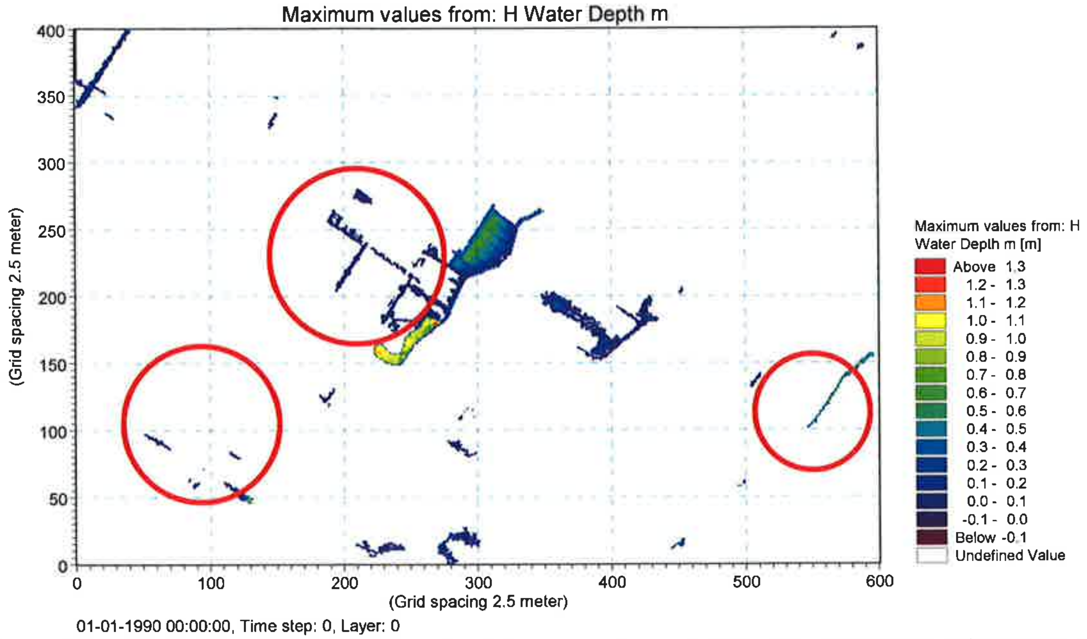


Figure 53. **Maximum water depth over simulation period for cut Mike Flood model showing areas with significant differences from original model**

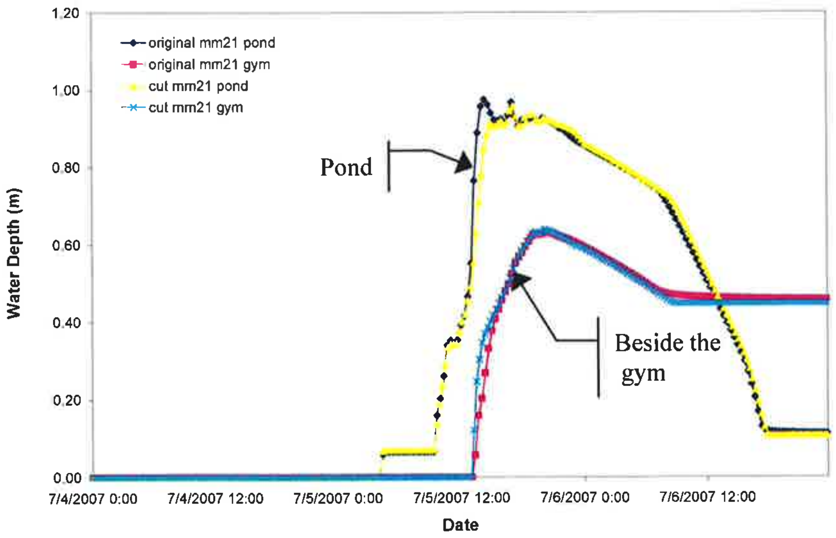


Figure 54. **Comparison of extracted time series from 2 points for original and cut models**

Analysis of the grid files of maximum water depths showed that total flood extent increased when the model was cut such that the number of inundated cells increased from 5065 to 5671.

Possible reasons for the bigger flood extent with the cut model are that since the entire network is interconnected, decoupling a part of it altered pressure heads and flows in the pipes causing the changes in the locations of flooding. The altered pressure heads due to the use of the virtual basins upstream instead of the topography drove the flow of water in a different way from the original model.

Thus, it can be said that cutting the Mike Flood model has rendered it inaccurate in terms of simulating the real flooding conditions in the study area. However, the hydraulic computations and processes it represents remain correct. Thus, it will still be valid for purposes of comparison with a MOUSE-Mike SHE model having the same extent, topography, and drainage system elements, which is what is aimed for in this project. And so, for this study, the cut Mike Flood model will be the one compared to the Greve Midt MMSHE model.

5.3.2. Greve Midt MOUSE-Mike SHE Model

Greve Midt is located adjacent and just below the lower Olsbaekken catchment. It has quite a big percentage of green areas for a city center. The topography is very flat and the groundwater table is also shallow in this part of Greve because it is just along the coast. The area has very similar overland and subsurface characteristics as lower Olsbaekken and so the MMSHE model for Greve Midt was built similarly as the Olsbaekken MMSHE model. The MMSHE model for Greve Midt was built following the procedure described in Section 2.3.

5.3.2.1. Greve Midt MOUSE Model

The existing MOUSE model was validated in preparation for coupling with the Mike SHE model. The nodes, links, and open channels/ditches that fell inside the selected model extent were extracted from data tables for preparing the ADP file. The urban sub-catchments were also identified and manholes within the domain were selected as subsurface drainage manholes for structures inside the sub-catchments.

5.3.2.2. Greve Midt Mike SHE Model

The Greve Midt Mike SHE model was built following the steps described in Section 2.3.2. Some components for this model that are quite distinct from the other models built in this study are described below. The other elements of the model not discussed in detail were setup in a similar manner as the previous ones following the procedures in Section 2.3.2.

a) Water Movement Modules

Based on the land surface and underground characteristics of Greve Midt, all the hydrological processes available in Mike SHE were activated for the model. These were:

- Overland Flow
- Unsaturated Flow
- Evapotranspiration
- Saturated Flow

b) Model Domain and Grid

The selected area was 1.5 km x 1 km (600 x 400 cells) covering the city center of Greve Midt where the most serious flooding has been observed. The grid size was kept at 2.5 m. for comparability with the Mike Flood model.

e) Topography

The DTM used in the model was the same one used in the Mike Flood model except that land values along the boundaries were not assigned for the Mike SHE topography. The topography not only shows the surface structures but also reflects the correct heights of the buildings and houses.

f) Overland Flow

Different Manning M values were assigned for built-up (M=32) and pervious areas (M=5). This was considered more realistic than the uniform value for the entire region given in the Mike Flood model. A distributed value for "Initial Water Depth" was also specified to give the correct initial conditions for a detention pond in the middle of the study area.

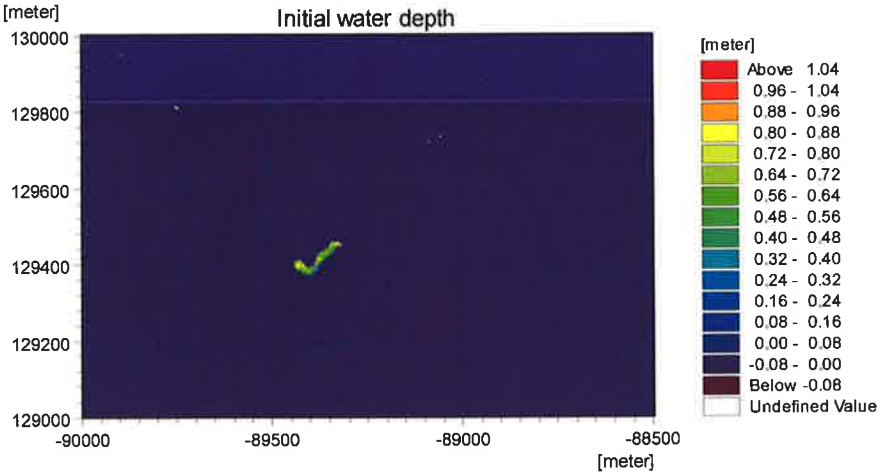


Figure 55. Initial water depth for Greve Midt MMSHE model to consider initial water level in the pond

g) Saturated Zone Drainage

Four (4) drainage manholes were identified in the model domain. Making the grid file for the drain levels for the buildings was not easy because the buildings had had their actual heights. This means that different drain levels (building height plus 2 meters) should be assigned for each building. The procedure for preparing the grid file is described in Section 2.3.2, item i).

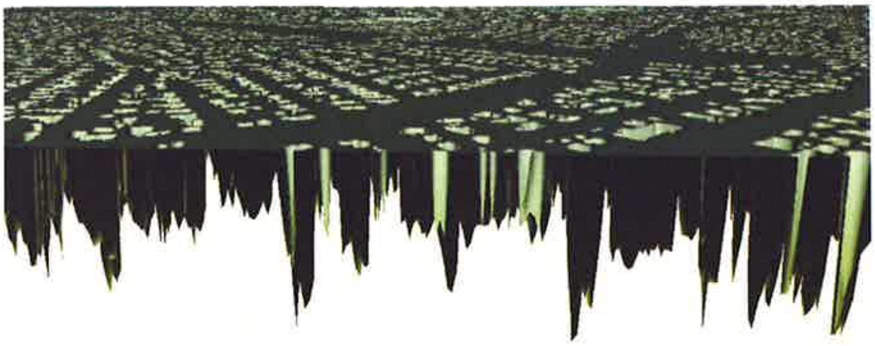


Figure 56. Greve Midt Mike SHE model drain levels

5.3.2.3. Coupling the Two Models

A PFS file was prepared for the Greve Midt MMSHE model and specified in the "Extra Parameters" section of the Mike SHE model. The PFS file refers to the MOUSE model and contains information on the drainage codes and corresponding drainage manholes for the saturated zone drainage section in the Greve Midt Mike SHE model.

The MOUSE model was coupled with the Mike SHE model by specifying an ADP file in MOUSE. The ADP file contained the list of nodes and links from the Greve Midt MOUSE model which fell within the Mike SHE model domain and should be linked to it. Selecting the appropriate nodes and links to be coupled was facilitated by copying the table of linked nodes from the Mike Flood model, which, unlike Mike SHE, has a "linking" tool that automatically selects the nodes of a big MOUSE model that fall within the coverage of the bathymetry.

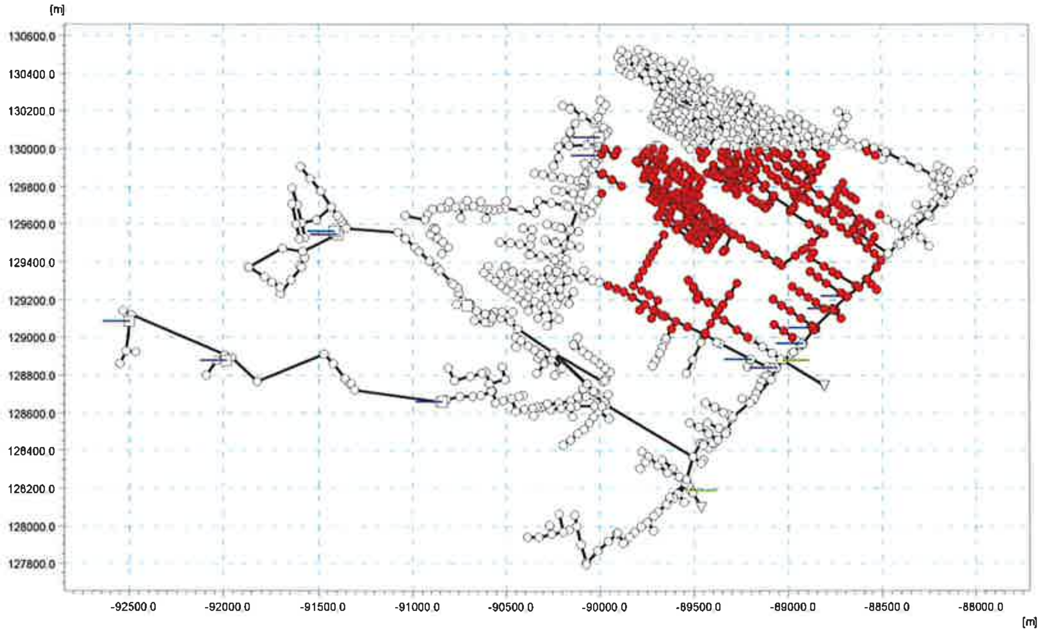


Figure 57. Coupled nodes and links for Greve Midt MMSHE model

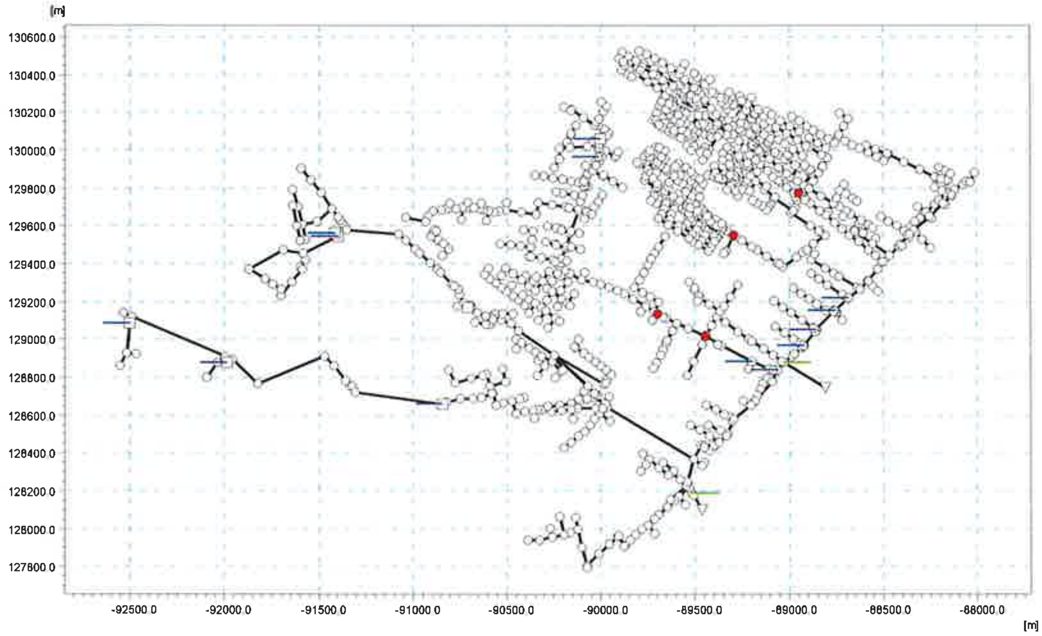


Figure 58. SZ drainage manholes for GreveMidt MMSHE model

6. SIMULATIONS AND RESULTS

After building the various models, preliminary simulation runs were performed in order to check for possible errors. Troubleshooting and corrections to the models were then made based on the pre-processing and preliminary results. Then actual model runs were performed using initial sets of parameters. Simulation results were extracted and analyzed according to the various objectives of the project. Results of the Olsbaekken MMSHE models were compared and evaluated against available observed values, while Greve Midt MMSHE model results were compared to those of the Greve Midt Mike Flood model.

6.1. Initial Simulations

The detailed lower Olsbaekken MMSHE model was the first model built in the project and so corrections and adjustments were mostly identified from initial simulations with this model. The flood event in the Olsbaekken catchment in 2007 occurred on the 5th of July, and so the simulation period for trying to reproduce the event was set from 20 June to 8 July 2007.

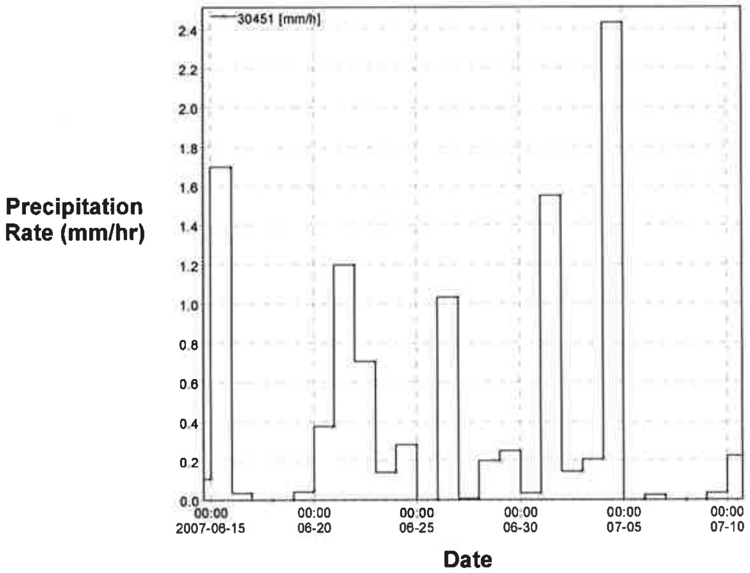


Figure 59. **Rainfall time series during 20 June - 8 July 2007 used for simulating July 2007 flood event**

Simulation results show the occurrence of water on the surface in areas where basins are located, in open green areas, and around natural channels. Areas where basins were located in MOUSE were filled with water and the stream running through the catchment has been defined by the concentration of water inside the channels. Water was seen to accurately accumulate in low areas and depressions and flow overland following the topography which was defined with a relatively high resolution (5 m) in the horizontal direction.

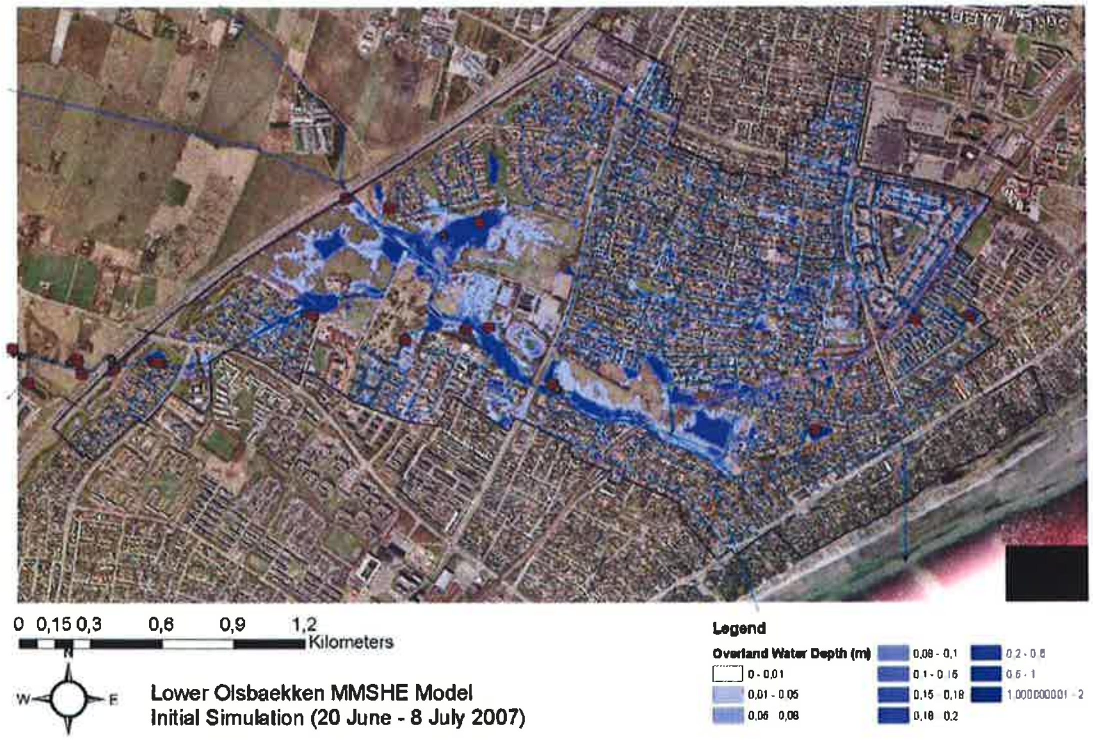
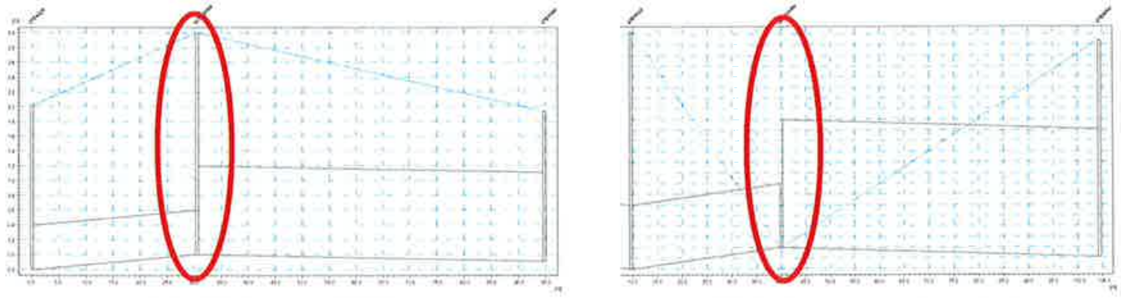


Figure 60. **Initial simulation results showing maximum water depth for lower Olsbaekken MMSHE model**

However, it was noted that the topographical depressions detaining a lot of the water were the basins that have been included in the MOUSE model. This means that these areas are being considered twice—in the topography of Mike SHE and in MOUSE. More water will be needed to fill the depressions because the water goes into the basins first, and then when they are filled up to capacity, goes out onto the surface and, again, accumulates in the depressions. Since they are quite large in size the water balance error that they cause can be quite significant. So, it was decided that the basins should be removed from MOUSE. This was accomplished by changing the basin nodes into simple manholes with zero heights in MOUSE and then specifying the old invert levels as the new ground levels.



(a) With basin in MOUSE (b) Basin converted to manhole

Figure 61. **Basins in MOUSE converted into manholes**

Simulation results (with the same set of boundary conditions) of the MMSHE model without the basins in MOUSE show that the extents of maximum overland water are wider and the depths are higher. For example, in one of the areas with the "basins", the difference in maximum water depths was around 0.5 m.

(a) Before MOUSE basin removal (b) After MOUSE basin removal

Figure 62. **Water depth in a topographical basin before (a) and after (b) basins were removed in MOUSE**

All the MOUSE models subsequently used in building the other MMSHE models in the study were corrected in a similar manner.

6.2. Olsbaekken MOUSE-Mike SHE Models

Simulation results using the MMSHE models for Olsbaekken were analyzed and compared with available observed values in order to evaluate if this flood modelling approach performs well and is appropriate for combination rural-mixed urban areas.

6.2.1. Detailed Lower Olsbaekken Model

Analysis of the performance of the Detailed Lower Olsbaekken MMSHE model focused on the period 15 June – 8 July 2007. Two sets of simulations were performed—one with antecedent conditions (using "hotstart" results from January 2007), and one without "hotstart" and using equilibrium conditions according to soil properties as initial conditions.

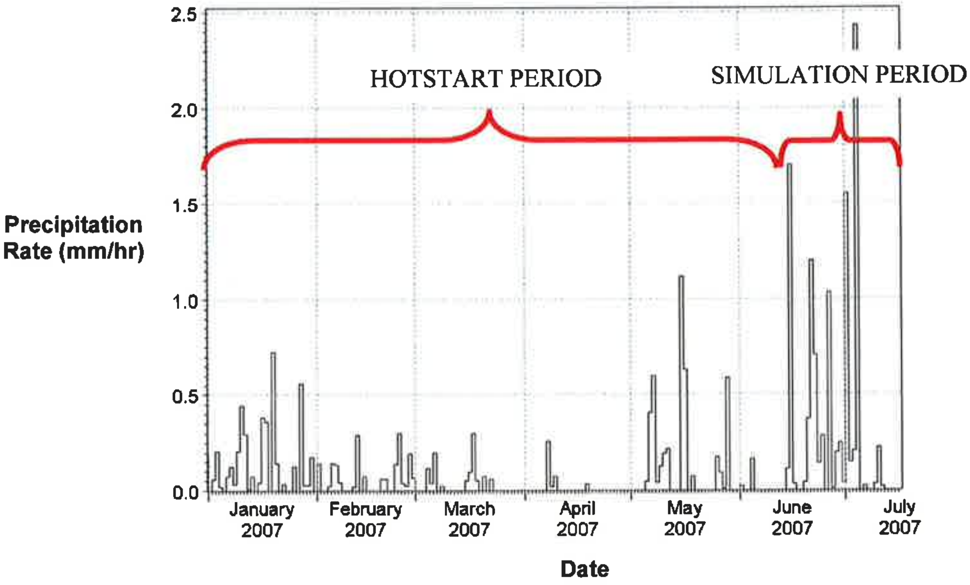


Figure 63. **Rainfall time series used for simulations**

Without Hotstart

Simulation results for the period 15 June – 8 July 2007 showed occurrence of overland water in low open areas which was also observed during the event. No flooding was seen in Godsparken, where flooding reportedly occurred in July 2007 (inside the red circle on the figure below).

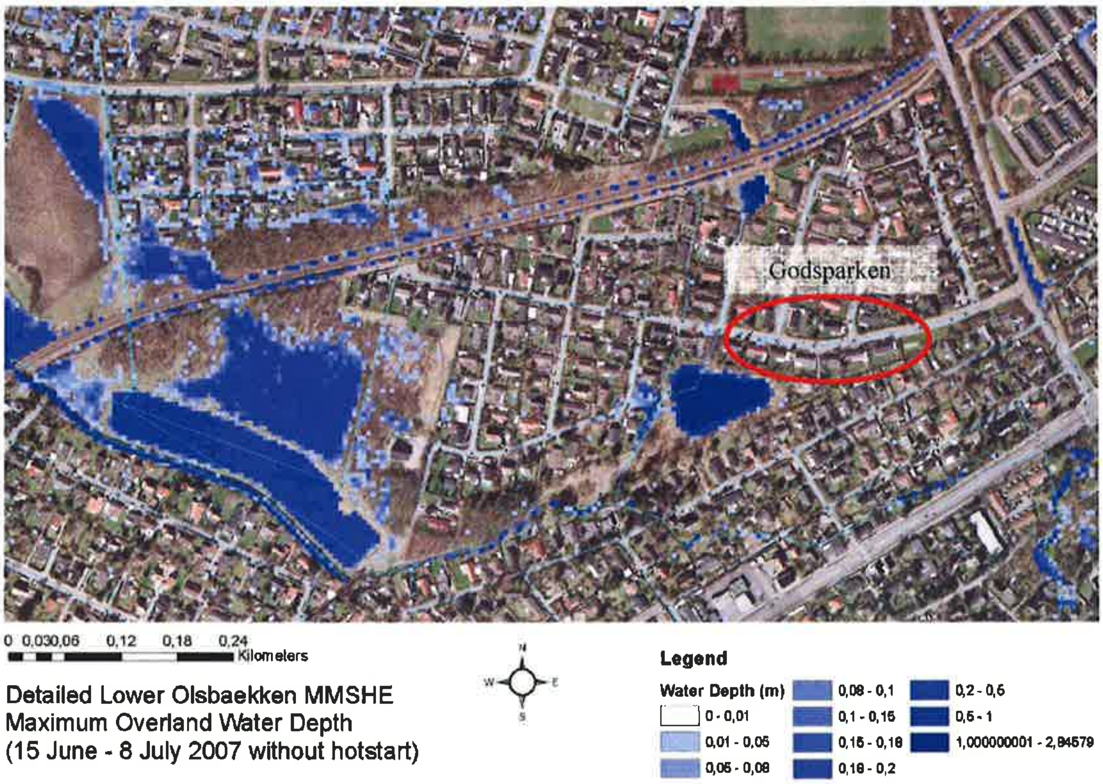


Figure 64. Maximum overland water depth for lower Olsbaekken MMSHE model without hotstart; No flooding resulted in Godsparken

With Hotstart

It was surmised that results from the MMSHE model will be improved by considering antecedent hydrological conditions in the study area at the start of the simulation period. In the previous case (without hotstart) initial hydrological conditions were based on specified initial potential heads and equilibrium conditions derived from soil pressure-moisture content relationships. To start the simulation with possible actual hydrological conditions, the model was run for 6 months from January to June 2007 and then the results in terms of water content in the unsaturated zone, groundwater heads and overland water levels were used as the starting point (hotstart) for the simulation from 15 June to 8 July 2007.

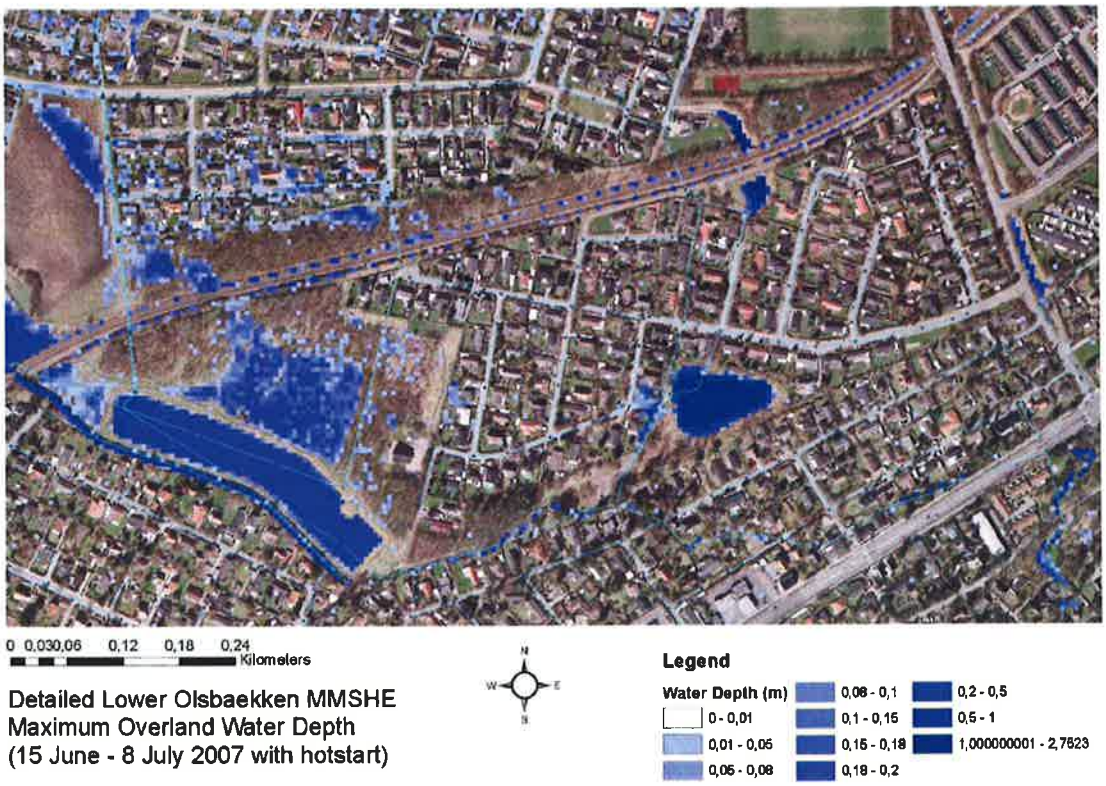
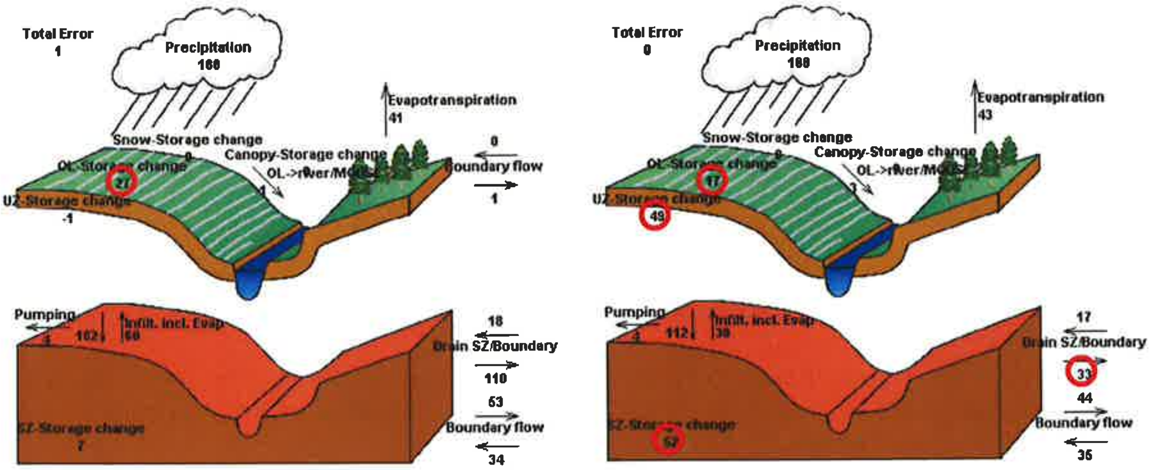


Figure 65. **Maximum overland water depth for lower Olsbaekken MMSHE model with hotstart; Shows no flooding in Godsparken and less water than simulation without hotstart**

However, simulation results actually showed less water on the surface than for the simulation without hotstart. To check, water balances were extracted for the results with and without hotstart and compared to each other.



(a) Water balance for simulation without hotstart (b) Water balance for simulation with hotstart

Figure 66. **Comparison of water balances for simulations without (a) and with (b) hotstart**

For the simulation with hotstart, it seemed that most of the water infiltrated into the ground and replenished the unsaturated and saturated zones as can be seen from the high amounts of storage change in the UZ and SZ zones in the water balance. Low initial head levels underground may have also caused limited exchange of water between the saturated zone and the drainage network as indicated by the low "Drain SZ/Boundary" value in the one with hotstart compared to the one without hotstart.

The reason for this may have been that initial hydrological conditions from the January – June 2007 simulation results used as hotstart showed big deficits in unsaturated and saturated zone storages. The combination of boundary outflows due to saturated zone boundary conditions and drainage into MOUSE significantly lowered groundwater levels, and when these conditions were used as initial conditions for the succeeding simulation (15 June – 8 July 2007), the deficits had to be filled.

Using the results of the January – June 2007 simulation as initial conditions for the flood event simulation was more correct than starting the simulation without hotstart, but:

- The same MMSHE model (with the same domain) was used in generating the hotstart but according to the Municipality, the hypothesis is that flood waters during the 2007 event came from the saturated green areas upstream. So, upstream soil moisture conditions could be the major factors that caused flooding in lower Olsbaekken, and thus, antecedent soil moisture conditions in the upper catchment must be the factors considered in running the Detailed Lower Olsbaekken MMSHE model.
- Great deficits in water in the underground layers may have resulted from the relatively low percentage of pervious areas in the lower Olsbaekken catchment as well as the assumption that all the buildings and houses had basements and underground drainage. These conditions essentially caused the dearth of water infiltrating into the ground and the high drainage of groundwater into the MOUSE network due to underground drains.

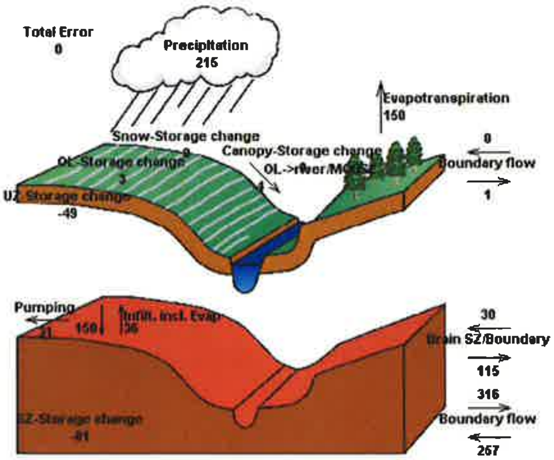


Figure 67. Initial conditions from January – June 2007 simulation used for hotstart

Water level observations during the simulation period were available for two points in the study area: Station OL1 and Station OL2. These points corresponded to natural channel links Olsbaek_452711 and Olsbaek_521511 in the MOUSE model.

Figure 68. Locations of water level observation points in Lower Olsbaekken

Comparison of simulated with observed values showed similar water level variation patterns. However, there were big differences in peaks throughout. At the beginning of the simulations computed water levels were generally higher than observed, and at the end simulated water levels were lower. The greater amount of water in the model for the simulation without hotstart compared to the one with hotstart was also apparent. It is clear that the Detailed Lower Olsbaekken MMSHE model needs to be calibrated because the initial conditions that have been set for the model were based on general assumptions and estimates about the characteristics of the study area.

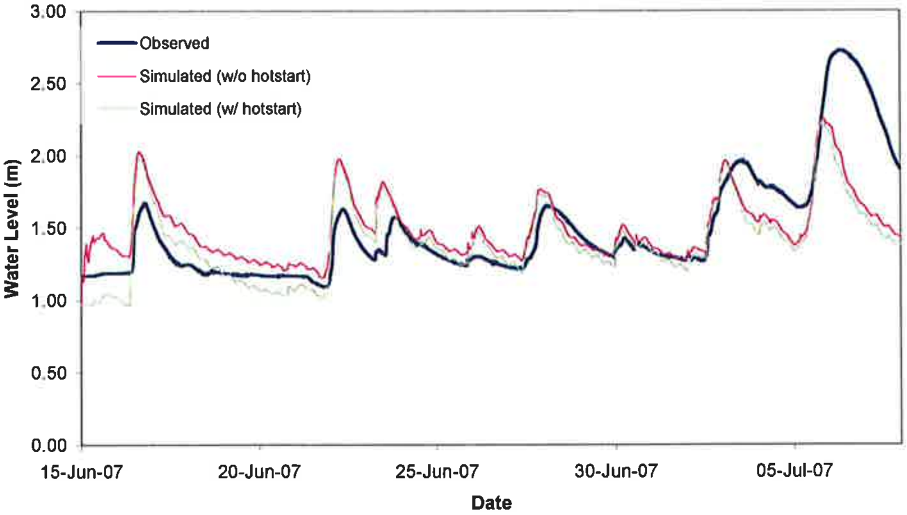


Figure 69. Comparison of observed and simulated water levels in Station OL1

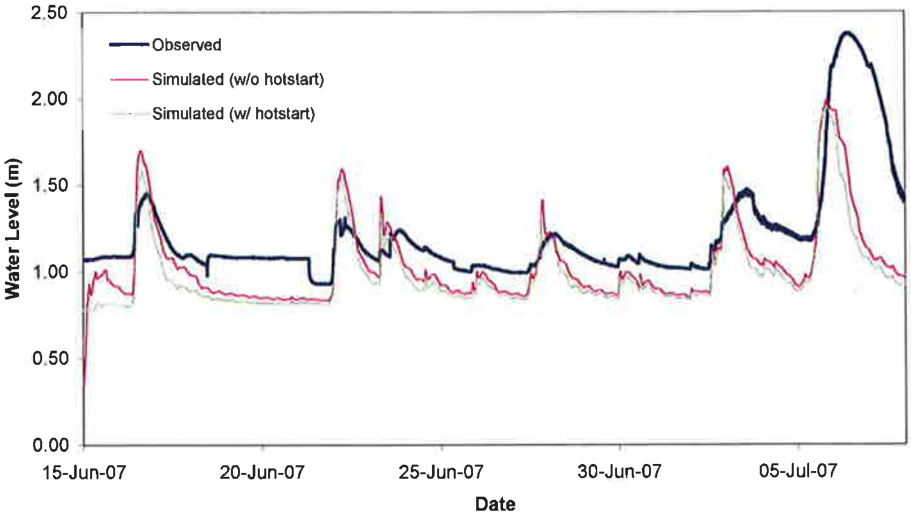


Figure 70. Comparison of observed and simulated water levels in Station OL2

6.2.2. Comparison of Overall Olsbaekken and Detailed Lower Olsbaekken Models

Results of simulations with the Detailed and Overall Olsbaekken MMSHE models for the period 20 June-8 July 2007 were used to compare the two models to each other and evaluate their performance.

Figure 71. shows simulation results from the Overall MMSHE model. It shows the maximum overland water depth during the simulation period, which reached a maximum value of 3.36 m in a pond/basin area upstream.

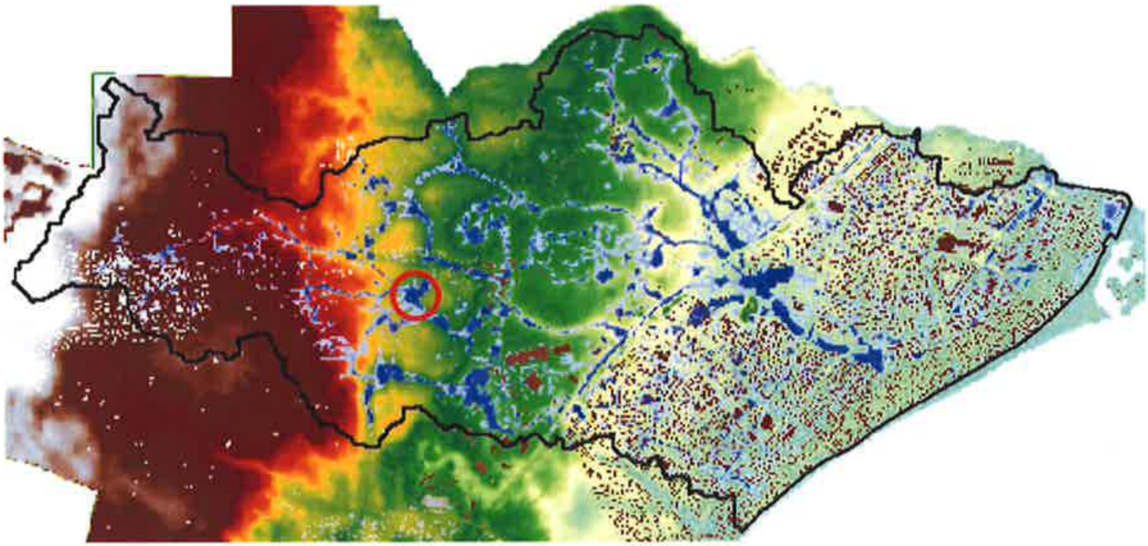


Figure 71. Maximum OL water depth coverage for Overall Olsbaekken MMSHE model showing area with highest depth

Focusing on the area also covered by the Lower Olsbaekken MMSHE model, it has been observed that the overall model shows more water overland than the detailed model.

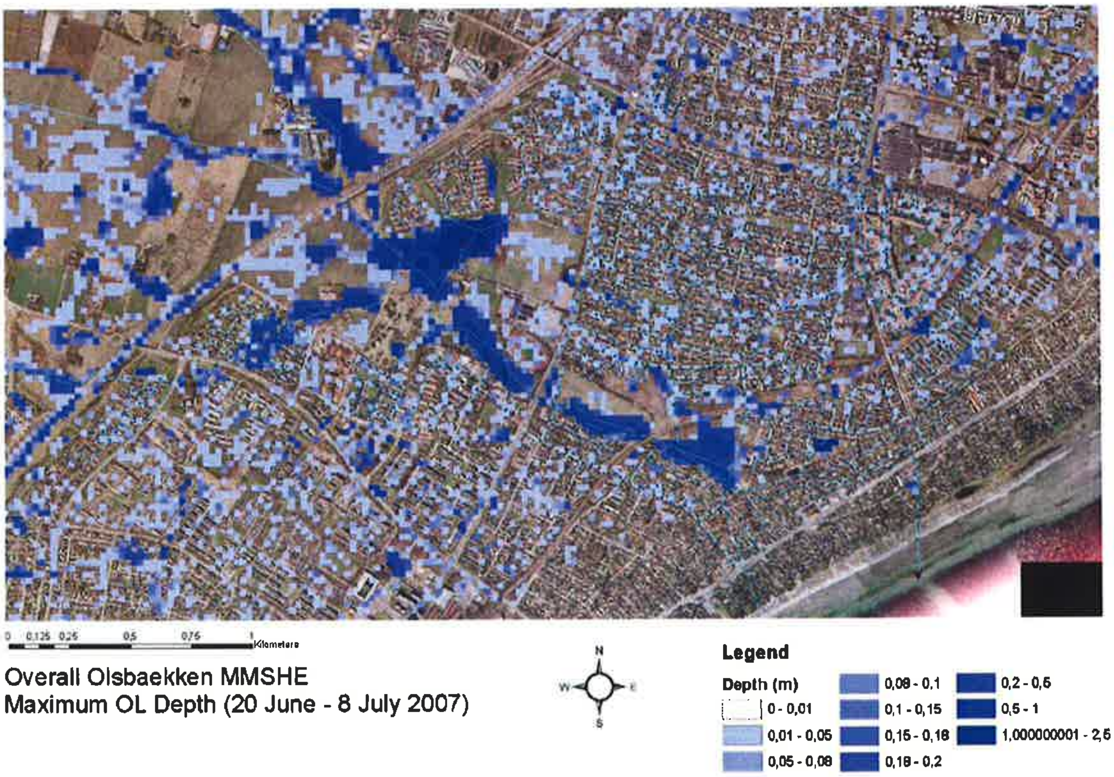
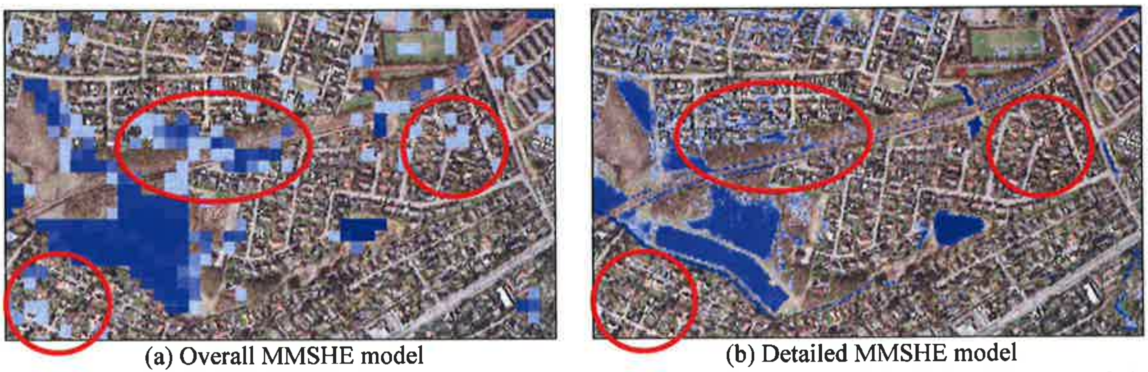


Figure 72. **Results of the Overall MMSHE model in the lower Olsbaekken area**

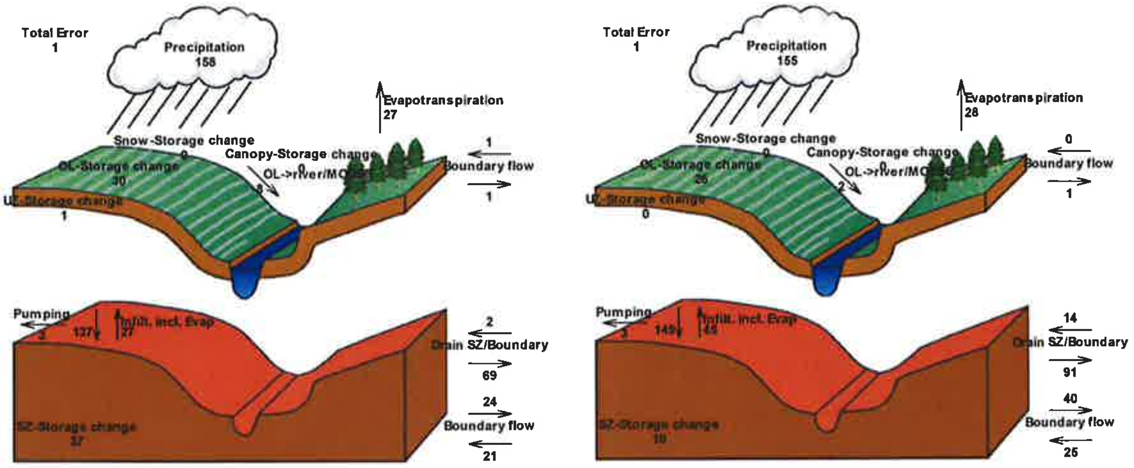
Looking at the results in the area in Lower Olsbaekken where there was serious flooding in 2007 (called Godsparken), it was more clearly observed that there was more overland water with the Overall MMSHE model.



(a) Overall MMSHE model (b) Detailed MMSHE model

Figure 73. **Comparison of maximum overland water for overall (a) and detailed (b) MMSHE models in Godsparken showing areas with significant differences**

To confirm these observations, the water balance for the two models over the lower Olsbaekken area were extracted and compared to each other.



(a) Overall MMSHE model (a) Detailed MMSHE model

Figure 74. Comparison of water balance in Lower Olsbaekken area for overall (a) and detailed (b) MMSHE models (units in mm)

For the Overall model, the water balance for the Lower Olsabekken area was extracted from the results by estimating the coverage of the Detailed model on the Overall model. But since the Overall model had a bigger grid size than the Detailed model, slight differences in some components could be observed for the water balances (because coverage was slightly different). For example, there is a difference of 3 mm for Precipitation and 1 mm for Evapotranspiration. However, these slight differences may be explained by the difference in extents of the extracted water balances. The much greater Saturated Zone storage in lower Olsbaekken with the Overall model could be explained by the less drainage into MOUSE ("Drain SZ/Boundary") that occurs in the Detailed model. This could, in turn, be explained by the less "contact" between the drainage network and the groundwater table in the Overall model due to averaging of calculations over bigger grids.

Based on the "OL Storage Change" values, it was found that there was more overland water in the Overall model, which had 30 mm over the Lower Olsbaekken area compared to 26 mm for the Detailed model.

The reason for the greater amount of water on the surface for the Overall MMSHE model may have been because it had more water in its drainage network because of additional inflows into MOUSE due to water exchange with the hydrological units (overland and saturated zones) in the upstream catchment. For the Detailed MMSHE model, inflows from the uncoupled upper catchments were computed solely with the MOUSE runoff model using specified percentages of impervious areas. For the Overall MMSHE model, inflow into the drainage network in the upper catchment not only comes from the MOUSE runoff model but also from the saturated zone and overland flow exchanges with Mike SHE.

Drainage system inflows for the Overall and Detailed models were compared and it was confirmed that there was more water in the MOUSE network of the Overall model.

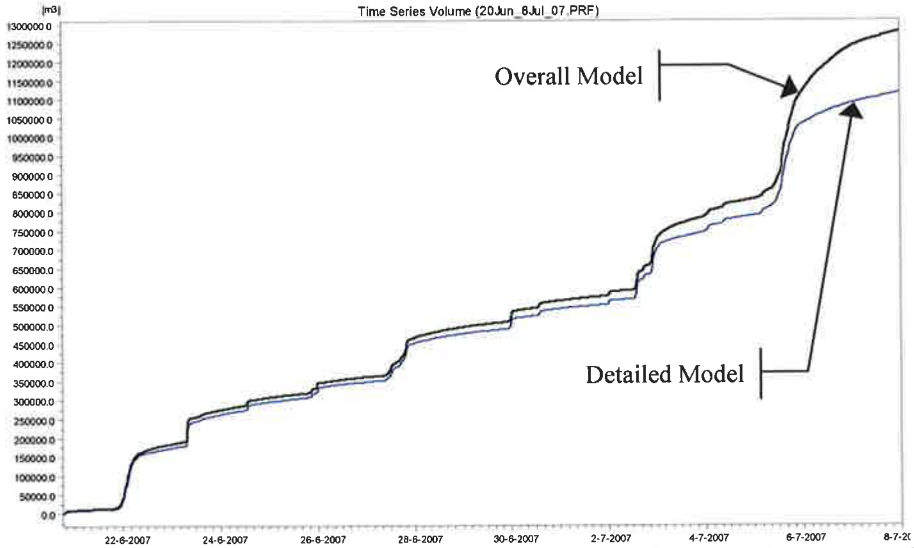


Figure 75. Accumulated inflows into MOUSE for Overall and Detailed MMSHE models

To determine the amount of water "missing" in the Detailed Lower Olsbaekken MMSHE model, the discharge time series through pipes at the upstream boundary of the lower catchment were extracted from the MOUSE results for both the Overall and Detailed MMSHE models.

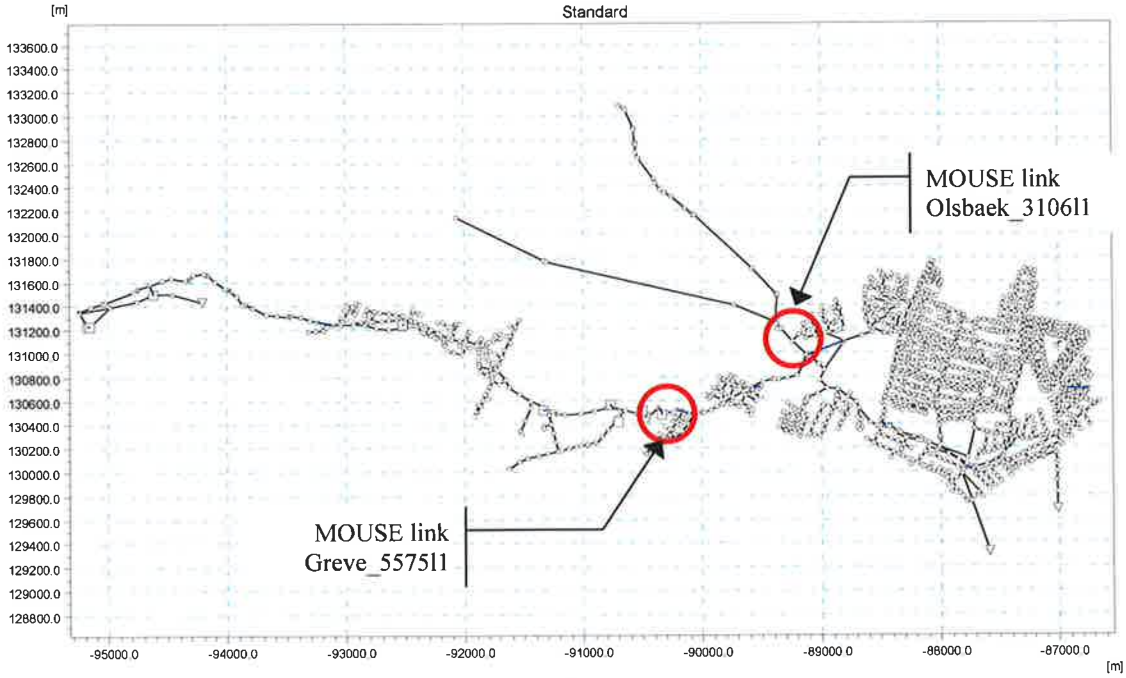


Figure 76. Locations of extracted pipe discharge time series (Links Greve_557511 and Olsbaek_310611)

It was found that discharges were generally higher through the pipes in the Overall model than in the Detailed model. In MOUSE link Greve_557511, the accumulated discharge volume was 511155 m^3 for the Overall model and 407814 m^3 for the Detailed model, and in link Olsbaek_310611 the accumulated discharge volume was 313083 m^3 for the Overall model and 141756 m^3 for the Detailed model. In total, there was around 33% more water entering the MOUSE network from the upstream areas at the boundary with the Overall model than with the Detailed model.

It was also noted that the greatest differences in inflows occurred near the end of the simulation period. This could be attributed to increasing soil moisture and groundwater levels, as well as the occurrence of overland flows in the Mike SHE model that encouraged higher flow exchanges with the pipe network in the upper catchment.

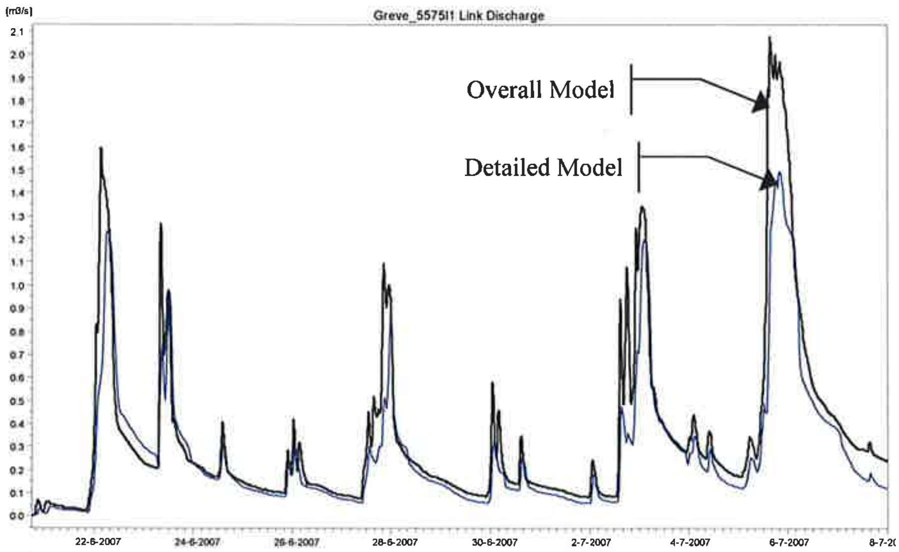


Figure 77. **Comparison of discharge through link "Greve_5575l1" for the Overall and Detailed models**

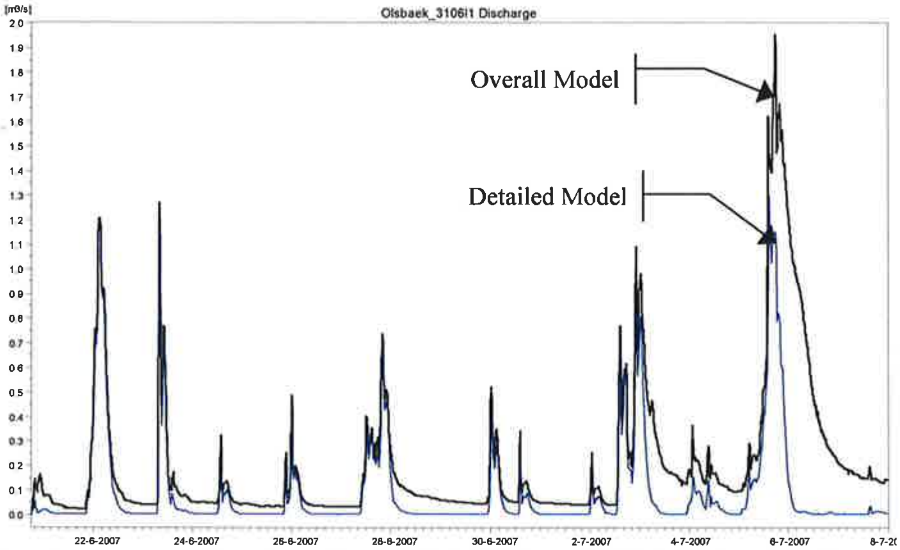


Figure 78. **Comparison of discharge through link "Olsbaek_3106l1" for the Overall and Detailed models**

However, despite observing the accumulation of big amounts of overland water in many places with the Overall model, no flooding was seen in Godsparken—the area that was reported to have been flooded in July 2007.

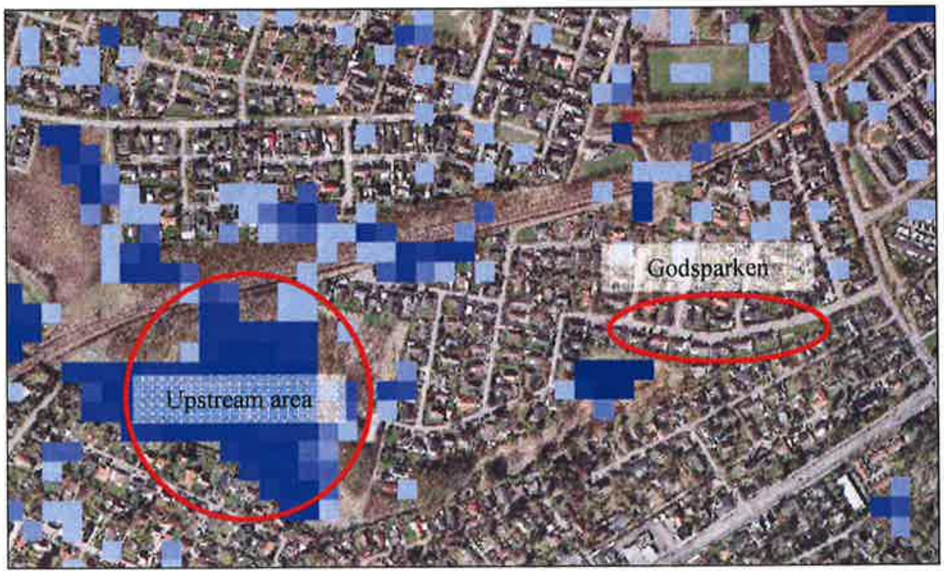


Figure 79. No flooding observed in Godsparken with the Overall MMSHE model

But a big concentration of water ("ponding") was observed upstream of Godsparken to the southeast, which is where a natural and an artificial waterway run side-by-side. It has been hypothesized by the Municipality that flood waters during the 5 July 2007 event originated from this place and flowed along the streets towards Godsparken.

However, simulation results seemed to show that water was just accumulating in the upstream area. Reasons for this could be that the amount of water in the system is still not accurately represented (that we are "missing" water). A closer look at the simulation results revealed that the water elevation in the upstream area at the edge of the "ponding" was about 2.07 m while land elevation in Godsparken was about 1.99 m. Based on the hypothesis about the cause of the flood, the Overall MMSHE model should have water from the upstream area finding its way down to Godsparken, but then 0.08 m elevation difference may not be enough to cause flooding in Godsparken.

Flow paths that should be in the topography could also have been not reflected accurately in the model preventing the movement of water from the upstream area to Godsparken. The topography around the Godsparken area was analyzed to determine if this was happening.

The topography, well-represented by the 5-m grid topography grid file, clearly showed low-elevation areas defining possible flow paths for overland water to follow from the upstream area towards Godsparken.

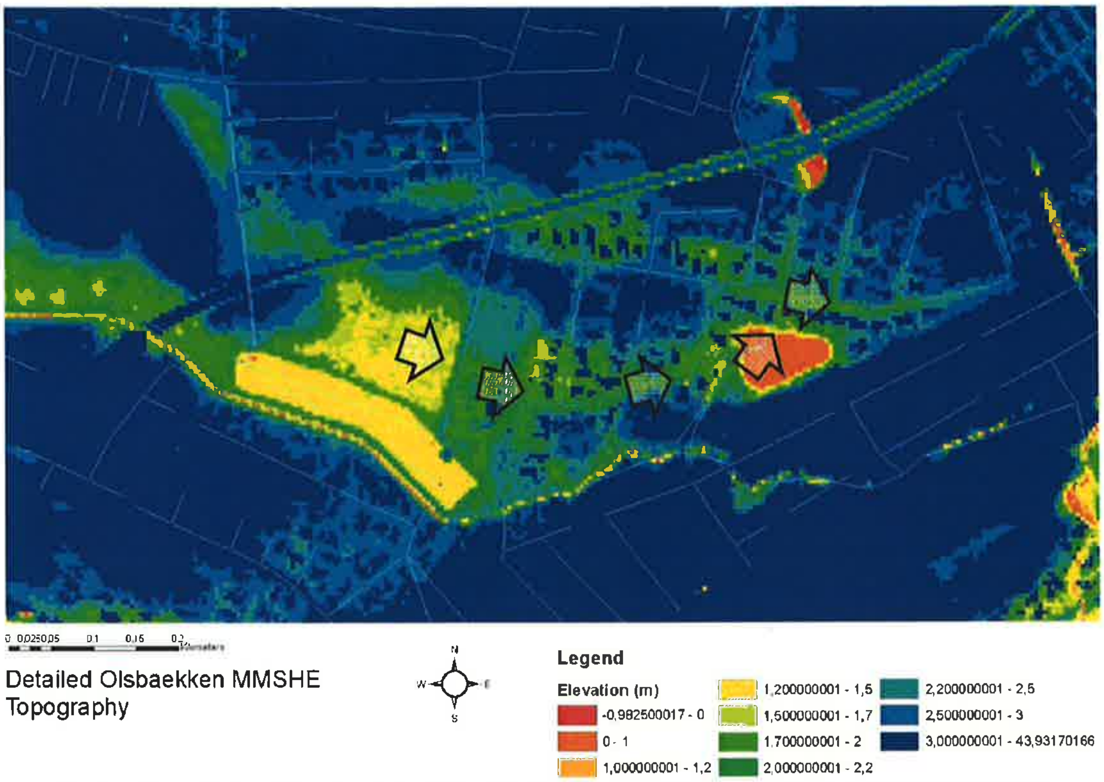


Figure 80. 5-m grid topography for area around Godsparken showing possible flow paths

However, the same flow path could not be clearly distinguished from the 25-m grid topography grid file used for the Overall Olsbaekken MMSHE model.

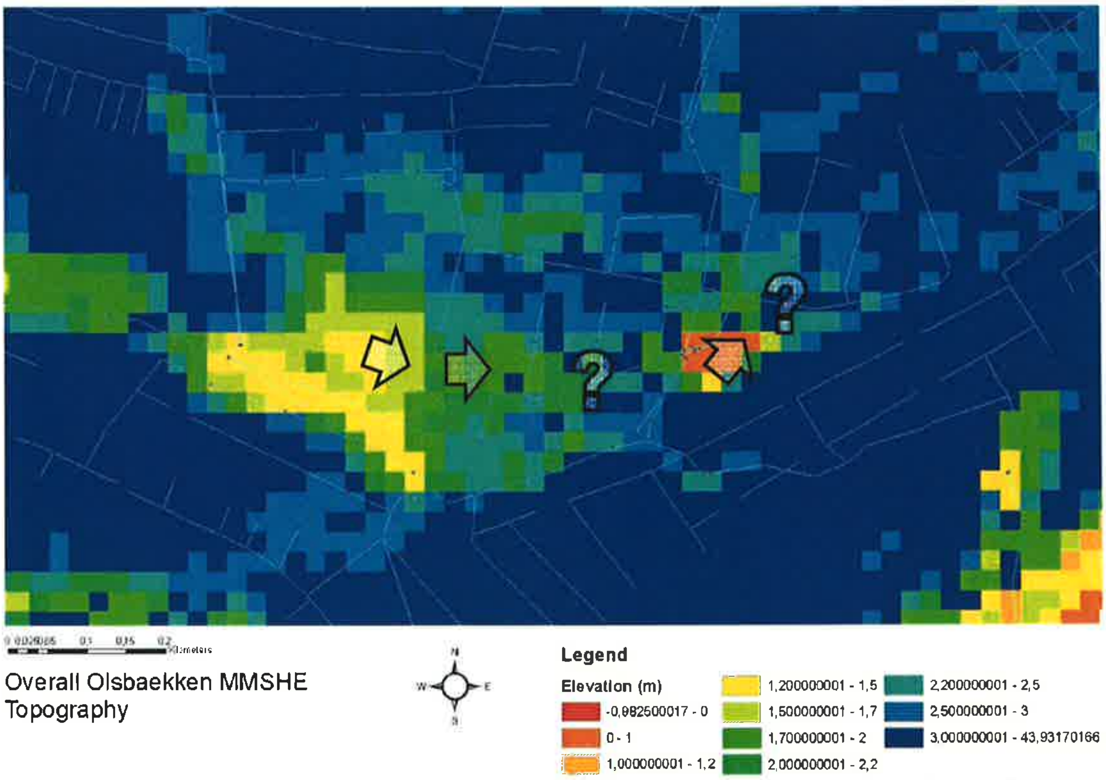


Figure 81. 25-m grid topography for Godsparken area showing no defined flowpath

In the topography file for the Overall model, narrow areas of low elevation defining possible paths for water to flow through could have been obliterated due to interpolation (averaging) of land elevations into a bigger grid size (from 5 m to 25 m). In addition, structure shapes that have been poorly converted into raster grids that have been reflected in the topography may hinder and cause poor simulation of overland flows.

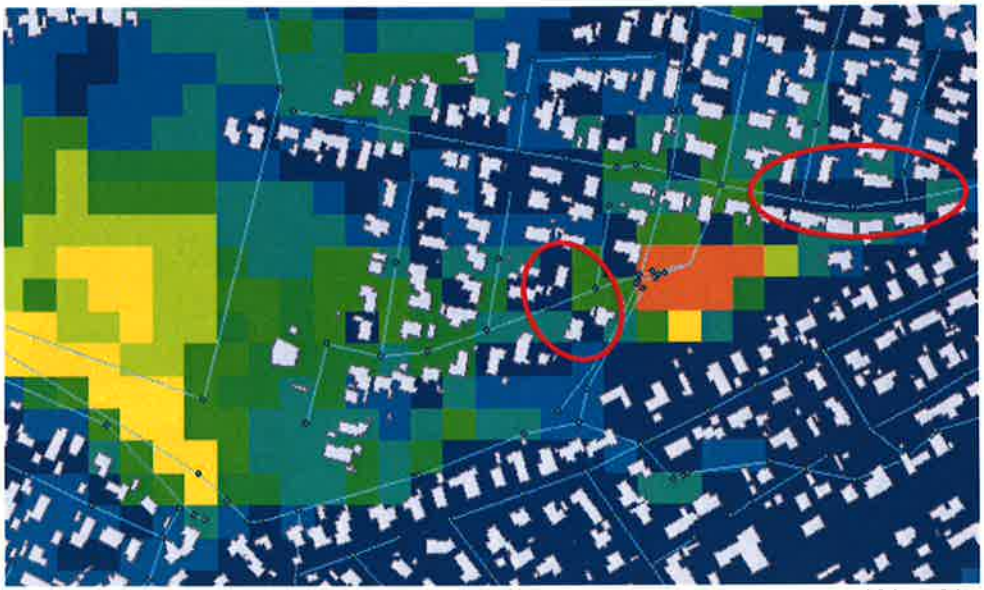


Figure 82. High elevations blocking flow paths due to interpolation of topography grid into bigger grid size (showing real shapes for structures)

Despite the better accuracy in reflecting inflows into the lower Olsbaekken area in using the Overall instead of the Detailed model, possible reasons for the inaccurate representation of the flood event are:

- The higher elevations in the upstream catchment affect rainfall over the area and the influence of elevation needs to be considered for the rainfall input
- The topography is not accurately described in the Overall model (because of the bigger grid size) preventing the accurate movement of water overland
- The hydrological and hydraulic parameters that have been initially specified are far from the true characteristics of the system and calibration is required

6.3. Comparison of Greve Midt Mike Flood and MMSHE Models

The Greve Midt MMSHE and Mike Flood models were run with the same rainfall time series over the same period (20 June – 8 July 2007) and the results were compared to each other in order to identify differences between the two methods. System characteristics and coupled nodes were kept the same for the coupled MOUSE networks in both models. The only apparent difference between the two was that since the MMSHE model had computational modules for different components of the hydrologic cycle, processes such as infiltration and evapotranspiration over impervious areas and groundwater flows were being considered in the MMSHE model but not in the Mike Flood model.

For initial comparison of results, the maximum overland water depths reached during the simulation period were extracted from results of both models. Visual comparison showed that there was greater flooding with the MMSHE model than the Mike Flood model.

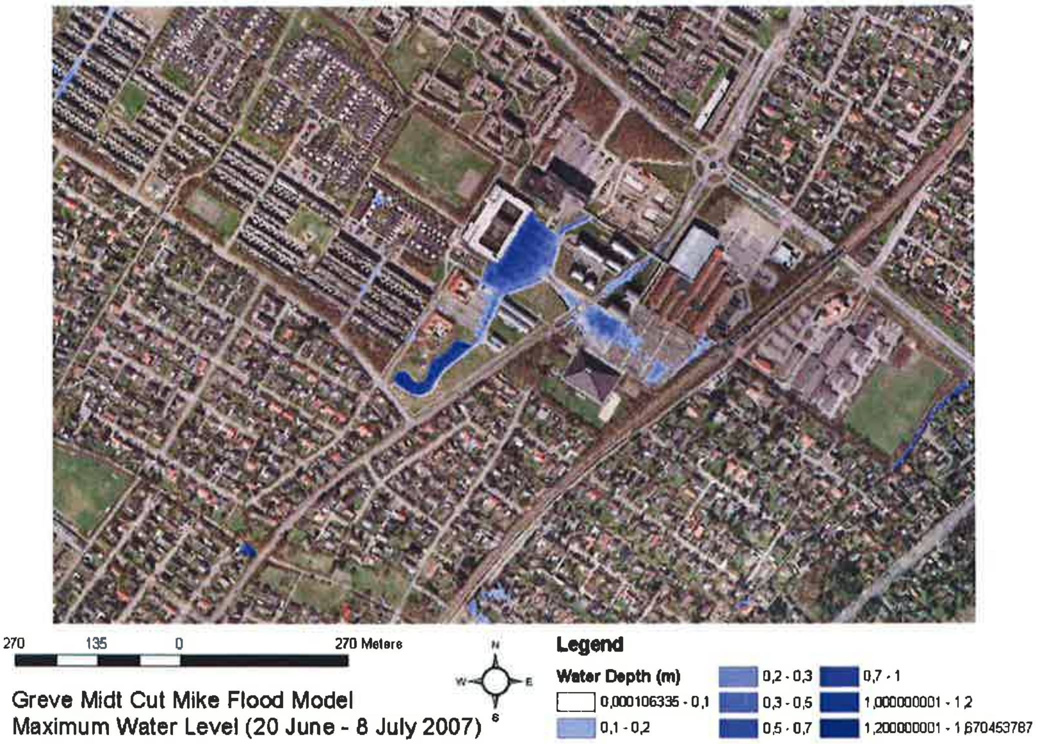


Figure 83. Greve Midt cut Mike Flood model results

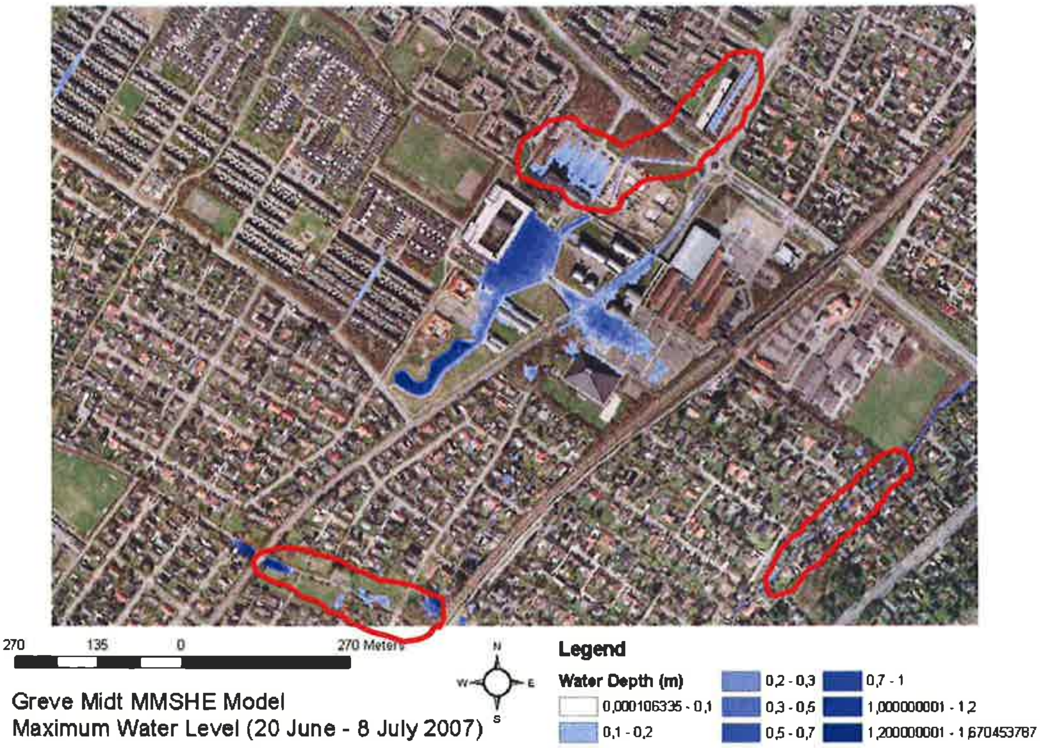


Figure 84. Greve Midt MMSHE model results showing flooded areas not flooded in Mike Flood model

Flooded areas in the Mike Flood model were also flooded in MMSHE and with bigger extents and higher maximum depths. In addition, several other areas were shown to be inundated in MMSHE but not in Mike Flood (encircled in red in Figure 84. above). Higher water depths (and volumes) with the MMSHE model are clearly observed from extracted water depths in a highly flooded area (beside the gym) as shown in the figure below.

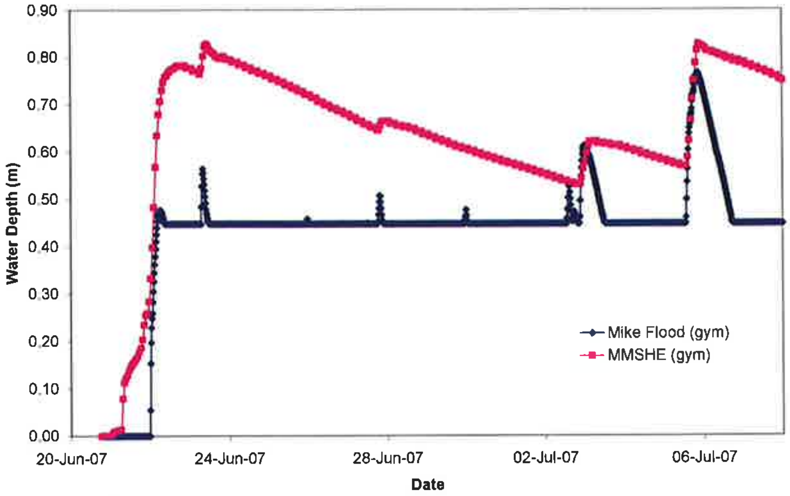


Figure 85. **Comparison of extracted overland water depths beside the gym for Mike Flood and MMSHE models**

The reasons for the higher amount of water occurring on the surface could be the inclusion of runoff over pervious areas in the MMSHE model as well as the drainage of groundwater into the pipe network, which were not present in the Mike Flood model. The maximum volume of water on the surface for the MMSHE model was about 20000 m^3, which was 40% bigger than in the Mike Flood model (which had about 11000 m^3) such that the volume difference between the two is about 8600 m^3. Checking the drainage models, there were also slightly higher inflows into MOUSE for the MMSHE model, which was 675592 m^3 or 8000 m^3 more than the 667531 m^3 inflow volume for the Mike Flood model. The increased occurrence of water on the surface seems to correspond well with the additional inflows into MOUSE and the remaining amount may have come from runoff from pervious areas that have been saturated.

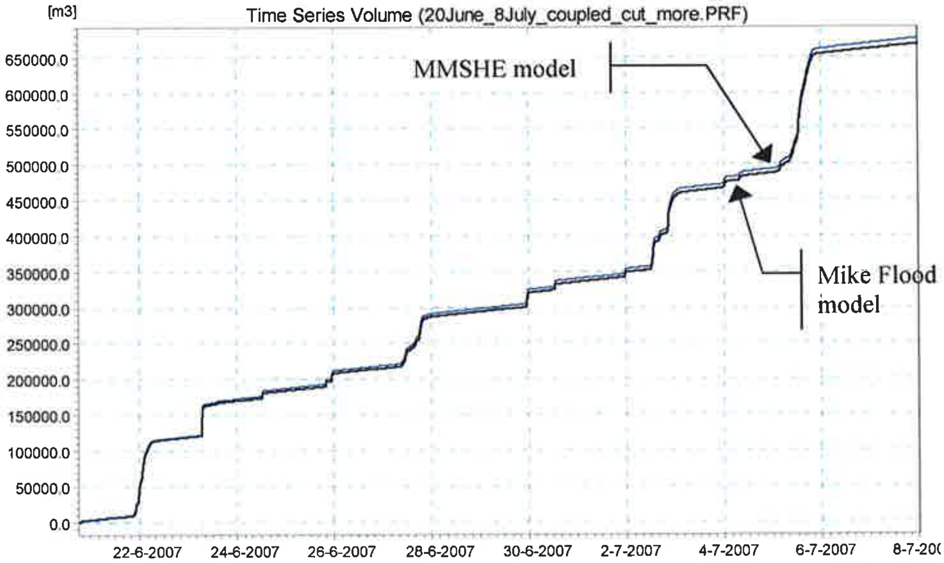


Figure 86. **Comparison of accumulated inflows into the MOUSE model for the Mike Flood and MMSHE models**

From the water balance calculations it was seen that infiltration into the saturated zone and underground drainage into MOUSE accounted for a major part of the water that occurred over the pervious areas considered in the Mike SHE model. A considerable amount of water (124 mm) was then introduced back into the system (through the drainage network) which would not have been accounted for if the movement of water through the green areas was neglected.

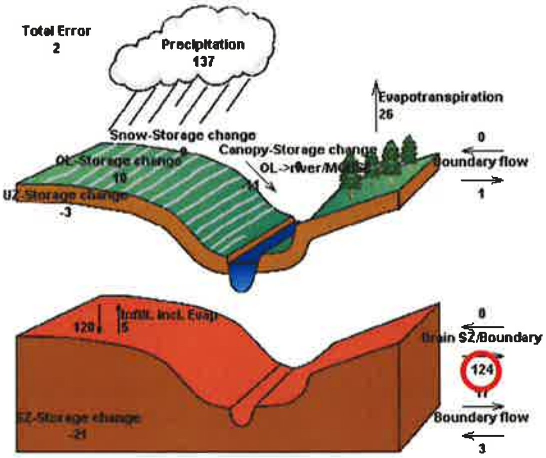


Figure 87. **Water balance for Greve Midt MMSHE model showing big outflow into MOUSE**

However, MOUSE-Mike SHE requires a greater degree of effort in setting up the model. There is a long list of data required for setting up a detailed Mike SHE model (as listed in Section 2.2) because land use, soil and aquifer characteristics are needed for UZ and SZ calculations. Mike Flood, on the other hand, has a very simple description of infiltration and evaporation and does not give a detailed description of infiltration into pervious areas and groundwater recharge. Coupling MOUSE and Mike SHE also requires much more effort because it does not have a coupling interface (like Mike Flood for coupling MOUSE and Mike 21) and that there are currently no available documents detailing all the steps required for building a MOUSE-Mike SHE model for urban flooding.

Another disadvantage of the MMSHE model is that it requires very long computational times. In the study, a 15-day simulation period required around 90 hours of simulation time compared to 26 hours for a Mike Flood model with the same domain. This could be because of the computational layers for the different hydrological processes included in the Mike SHE model. Related to this, the greater effort in completing the required computations for a Mike SHE model greatly limit the extent and computational grid resolution that may be used for the model. For example, in this study, the workable MMSHE model for Greve Midt that could be built was a mere 12% of the size of the original Mike Flood model that was available for the area. With a very fine computational grid (2.5 m), the calculations that had to be performed if the original domain was used were simply too much for the software and the hardware to handle.

7. CONCLUSIONS

The project aimed to develop and investigate the use of a new method for urban flood modelling which takes into account the movement of water through the whole hydrological cycle.

Coupled 1D-2D, hydraulic-hydrologic models were built using MOUSE and Mike SHE for the municipality of Greve in Denmark. This mixed-urban area has been subjected to flooding in the past and the MOUSE-Mike SHE models were implemented to try to properly simulate the July 2007 flood event in the area. It has been the hypothesis that big expanses of pervious green areas in the upper catchment that became saturated after a long period of rain caused flooding in the lower catchment in July 2007.

During the course of this study a procedure for building a MOUSE-Mike SHE model for urban flood modelling was documented and presented in Chapter 2. The Mike SHE specialists and handful of experts in MMSHE modelling at DHI, and individual software manuals were consulted in developing the detailed steps. There were three occasions for which the developed steps were used to build MMSHE models, and successful simulations with those models indicate that the steps are operative and valid. The documented procedure could then be used to build MOUSE-Mike SHE flood models for other mixed-urban areas or used as a reference in developing newer versions of the base softwares to easily accommodate model coupling procedures.

Regarding the side-task of using the new Terrain Dataset in ArcGIS for generating DTMs for urban flood models, the new method has proven extremely efficient in handling very large amounts of point data compared to the traditional IDW interpolation method. However, it has been found that the DTM from the Terrain method slightly differs from those made using the traditional IDW method. The accuracy of the DTM from the Terrain method is slightly affected by the different types and higher number of processes involved in the method compared to the IDW method. But the great efficiency by which the method generates DTMs from very large amounts of data would be terribly wasted if it were disregarded because it produces grids that are not exactly the same as those generated the traditional way. Thus, choosing the required accuracy for the topography grid must be made carefully and weighed against the practicality of using traditionally used methods.

For flood modelling in Greve, simulation of flood conditions in the Godsparken area in the Olsbaekken catchment during the July 2007 event was attempted by building MOUSE-Mike SHE models—one a detailed model focusing on the flooded lower catchment, and the other a relatively coarse model of the whole catchment which includes the green upper catchment. Simulations with the MMSHE model for Lower Olsbaekken showed that a coupled MOUSE-Mike SHE model is a workable new method for simulating flooding in mixed-urban catchments. The model is able to realistically describe the occurrence and movement of water over the surface—accumulating in areas of natural channels and flowing according to the terrain and around structures. Using correct initial hydrological conditions at the beginning of the simulation would give more accurate especially for catchments where flooding conditions could be greatly influenced by antecedent soil moisture conditions. However, soil characteristics and boundary conditions should be accurate in order to correctly reproduce initial conditions for the simulation.

Results of the Overall Olsbaekken MMSHE model have shown that not only is it important to take into account processes such as infiltration, groundwater movement, and saturated zone drainage in modelling flooding for a mixed-urban area, but also that the important contributing sub-catchments to the occurrence of water in the area must be included in the model in order to correctly simulate the volume of water in the system. A smaller detailed model would be an efficient way to analyze flooding in a certain area but correct boundary conditions should be specified. This can be achieved by running a bigger (but coarser model for efficiency) model and extracting boundary conditions from the results for input into the smaller model.

Comparison of the MOUSE-Mike SHE model with the Mike Flood (MOUSE-Mike 21) model of the Greve Midt area has shown that the two methods produce comparable results for the study area such that flooded areas in the Mike Flood model could be reproduced in a similar manner with the MMSHE model. However, the MMSHEmodel offers the possibility of taking into account runoff from pervious areas and time-varying exchange of water between the saturated zone and the drainage network. But these modules and functionalities considerably increase the computational effort required and limit the efficiency of a very detailed and extensive MOUSE-Mike SHE model. The level of detail and accuracy of results, model coverage, computational time, and computer power and software limitations need to be weighed against each other when trying to build a workable MMSHE model.

7.1. Recommendations for Further Studies

Simulation results have shown that the MOUSE-Mike SHE modelling method shows great promise as a new generation of urban flood modelling technique especially for cities with a big percentage of green areas. The method is more holistic and adaptable to a wider range of hydrological conditions. However, the current model presently does not give results in complete agreement with available observations which indicates that further studies need to be carried out wherein:

- Existing conditions in the study area are reproduced as closely as possible. Soil properties, initial potential heads, water level conditions at the boundaries, and correct rainfall time series need to be specified. New data on sea water levels and land cover characteristics during the flood event being simulated need to be included in the model in order to try to improve its performance. The rainfall time series used in the simulations also need to be checked as it has been hypothesized that the area and elevation variation in the catchment warrants a distributed rainfall time series and consideration of elevation effects.
- An overall MMSHE model covering all the catchments for the drainage network model must be run for a long period to generate initial conditions and boundary time series for a more detailed MMSHE flood model with a resolution fine enough to accurately describe the topography including flow paths and surface structures.
- Calibration of the model parameters is performed. Changes to parameters such as surface roughness, hydraulic conductivity, leakage coefficient, leaf area index, root depth, specific yield and specific storage may be required.

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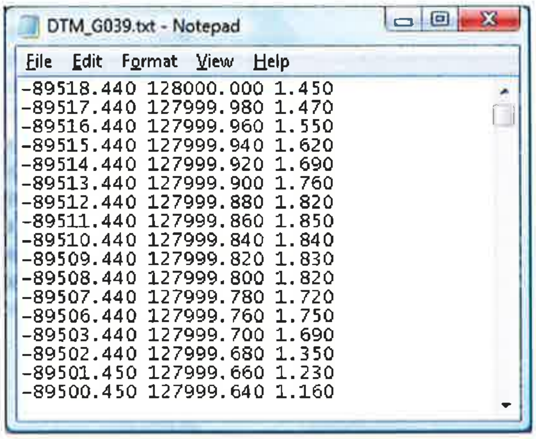
APPENDIX A. Generating DTM for Urban Flood Modelling

Digital terrain models (DTMs) are essential components of 2D overland flow models for flood modelling. The traditional method for building DTMs is the use of interpolation methods such as IDW (Inverse Distance Weighing) to generate a continuous surface from point data. However, point data can go up to millions in number for very large study areas or for when very accurate descriptions of the terrain are required (such as in urban flood modelling) such that a great number of point elevations are taken for a certain area. The traditional IDW method cannot handle such large amounts of data at one time. One technique that has been applied to get around this problem was to generate surfaces for small batches of point data and "sew" or mosaic them together to form the complete DTM. However, aside from being tedious, this method introduces uncertainties in areas where the small DTMs overlap and are put together. Thus, a new method for generating DTMs that is able to handle very big amounts of point data is required. ArcGIS has features called Terrains that make use of TIN (Triangulated Irregular Network)-based datasets that use geodatabase feature classes as data sources. Because of the way the data are organized, the interpolation and processing involved to generate the continuous surface are much faster than for the IDW method. With Terrain Datasets, millions of point elevation data can be used to generate a DTM in one go. A step-by-step procedure for building a DTM for urban flood modelling is presented in the succeeding sections.

A.1. Basic DTM from Point Data Using ArcGIS Terrain Dataset Method

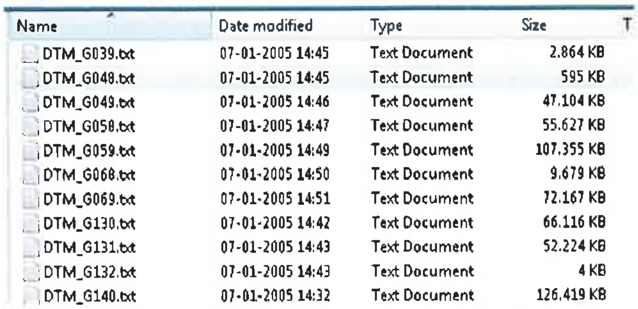
Step 1: Collect and prepare data. Basic data for making a DTM are usually 3D points in text format.



```
-89518.440 128000.000 1.450
-89517.440 127999.980 1.470
-89516.440 127999.960 1.550
-89515.440 127999.940 1.620
-89514.440 127999.920 1.690
-89513.440 127999.900 1.760
-89512.440 127999.880 1.820
-89511.440 127999.860 1.850
-89510.440 127999.840 1.840
-89509.440 127999.820 1.830
-89508.440 127999.800 1.820
-89507.440 127999.780 1.720
-89506.440 127999.760 1.750
-89503.440 127999.700 1.690
-89502.440 127999.680 1.350
-89501.450 127999.660 1.230
-89500.450 127999.640 1.160
```

Figure A-1. Point (x-y-z) data in text format

Usually, there are multiple text files for the DTM points for an area, and these may be combined for better data handling. The text files could be very big and combining them could be more easily done using the Windows Command Prompt.



Name	Date modified	Type	Size	T
DTM_G039.txt	07-01-2005 14:45	Text Document	2.864 KB	
DTM_G048.txt	07-01-2005 14:45	Text Document	595 KB	
DTM_G049.txt	07-01-2005 14:46	Text Document	47.104 KB	
DTM_G058.txt	07-01-2005 14:47	Text Document	55.627 KB	
DTM_G059.txt	07-01-2005 14:49	Text Document	107.355 KB	
DTM_G068.txt	07-01-2005 14:50	Text Document	9.679 KB	
DTM_G069.txt	07-01-2005 14:51	Text Document	72.167 KB	
DTM_G130.txt	07-01-2005 14:42	Text Document	66.116 KB	
DTM_G131.txt	07-01-2005 14:43	Text Document	52.224 KB	
DTM_G132.txt	07-01-2005 14:43	Text Document	4 KB	
DTM_G140.txt	07-01-2005 14:32	Text Document	126.419 KB	

Figure A-2. Multiple text files for the DTM of an area

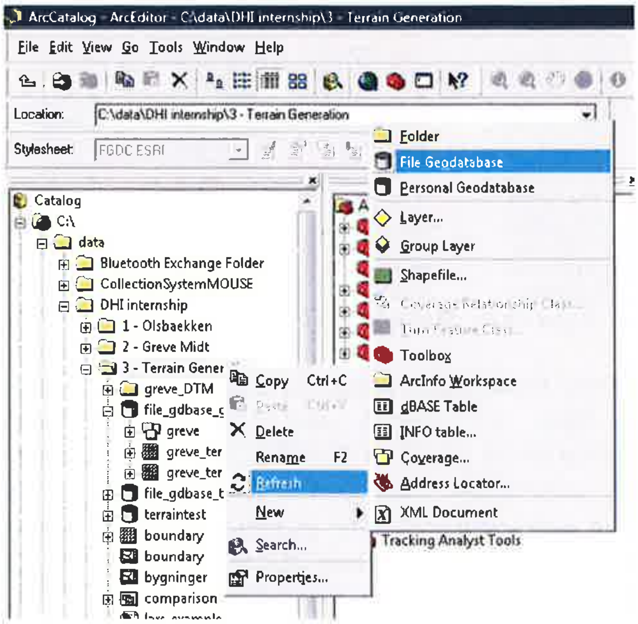
Gather the multiple text files in one folder. In Windows Command Prompt, go the folder where the text files are stored (i.e. C:\data\DHI internship\3 - Terrain Generation\greve_DTM\DTM_data). Select the correct text files and combine them into a new text file in the same folder. Edit the first text file in the list such that it will have x, y, and z headings. It is advisable that the text files to be merged have similar names so that they can be selected more easily, and that the name of the new text file be totally different from the other text files (i.e. ...> type DTM*.txt>greve.txt). This means all the text files with names starting with DTM should be combined into a new text file, greve.txt.

```
C:\data\DHI internship\3 - Terrain Generation\greve_DTM\DTM_data>type DTM*.txt>g
reve.txt

DTM_G039.txt


DTM_G048.txt


DTM_G049.txt


DTM_G058.txt
```

Figure A-3. Command prompt for combining multiple text files

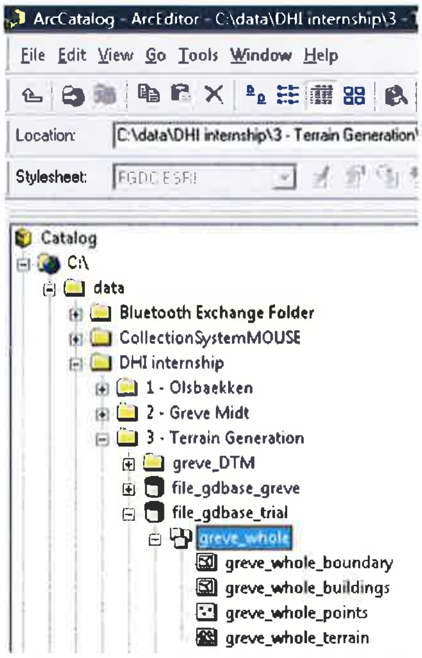
Step 2: Build the Geodatabase. Build a Geodatabase with a feature dataset that contains the feature classes that will be used to build the terrain and that will contain the terrain feature class to be built.

One can build SDE, personal, and file geodatabases. Personal geodatabases are the least capable and could be used for terrains with 20 million points or less. File geodatabases can be used for terrains with hundreds of millions of points. SDE is the most capable and appropriate for terrains whose point sets may grow into the billions.



Location: C:\data\DHI internship\3 - Terrain Generation

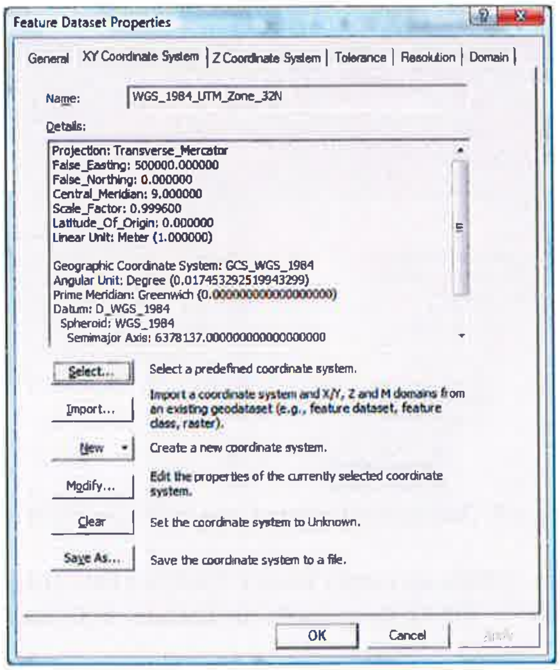
Figure A-4. Build a File Geodatabase



Location: C:\data\DHI internship\3 - Terrain Generation\

Figure A-5. Create a Feature Dataset inside the Geodatabase

The created feature dataset must be given a spatial reference including tolerance and resolution. The spatial reference for the dataset should be defined using a projected coordinate system. Use of geographic coordinates is not supported.



Name: WGS_1984_UTM_Zone_32N

Details:

```
Projection: Transverse_Mercator
False_Easting: 500000.000000
False_Northing: 0.000000
Central_Meridian: 9.000000
Scale_Factor: 0.999600
Latitude_Of_Origin: 0.000000
Linear Unit: Meter (1.000000)

Geographic Coordinate System: GCS_WGS_1984
Angular Unit: Degree (0.0174532925199433299)
Prime Meridian: Greenwich (0.000000000000000000)
Datum: D_WGS_1984
  Spheroid: WGS_1984
    Semimajor Axis: 6378137.000000000000000000
```

Select... Select a predefined coordinate system.

Import... Import a coordinate system and X/Y, Z and M domains from an existing geodataset (e.g., feature dataset, feature class, raster).

New Create a new coordinate system.

Modify... Edit the properties of the currently selected coordinate system.

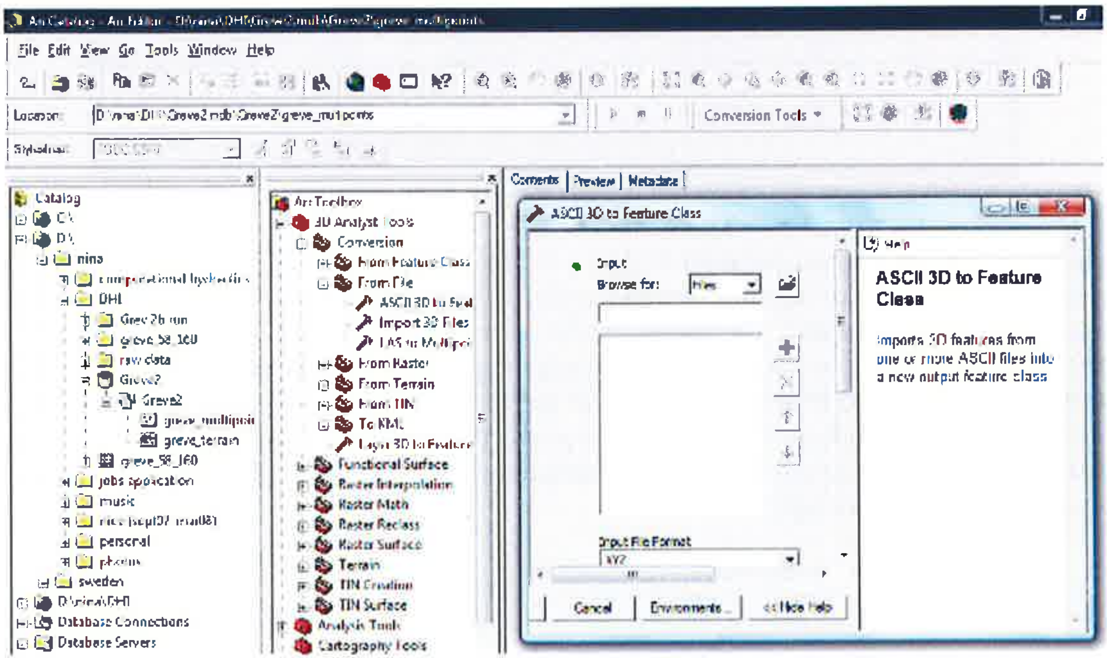
Clear Set the coordinate system to Unknown.

Save As... Save the coordinate system to a file.

Figure A-6. Specify spatial reference for the Feature Dataset

Step 3: Populate the Feature Dataset you created with 3D enabled data. Add your terrain measurements into one or more feature classes such as points, mass points, breaklines, etc. If your data is in ASCII format, use the "ASCII 3D To Feature Class" geoprocessing tool to import them.

If you have multiple text files for the point elevations, it is also possible to import the separate files into one feature class in the geodatabase, and so it may also be unnecessary to combine the text files into one file at the beginning as described in Step 1.



ASCII 3D to Feature Class

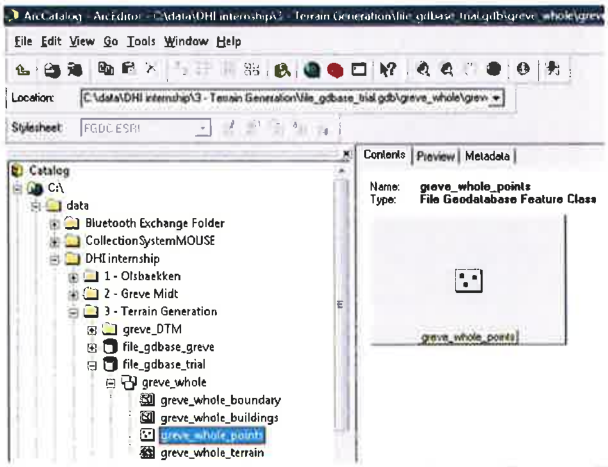
Input
Browse for: Files
Input File Format: XYZ

Help

ASCII 3D to Feature Class

Imports 3D features from one or more ASCII files into a new output feature class

Figure A-7. Import mass points with ASCII 3D to Feature Class tool



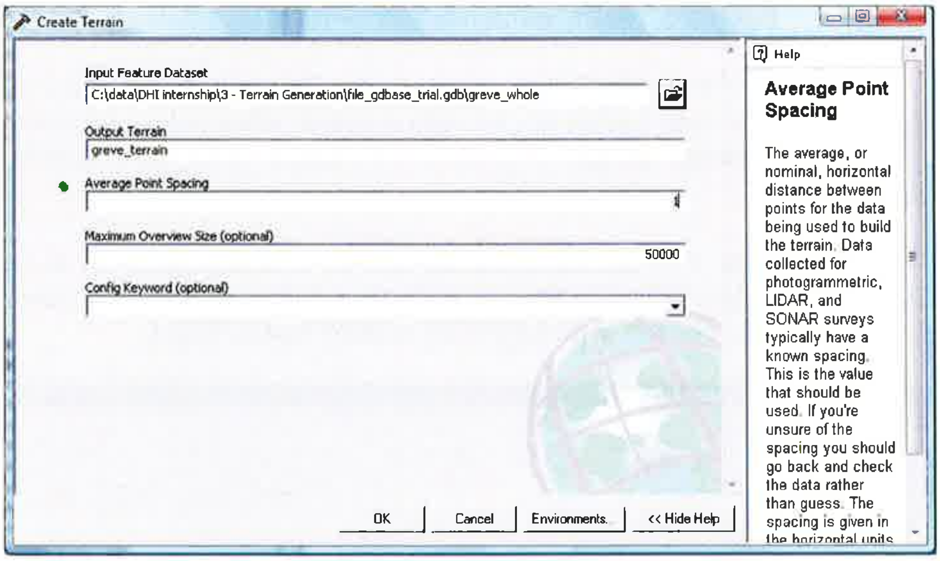
Location: C:\data\DHI internship\3 - Terrain Generation\file_gdbase_trial.gdb\greve_whole\grev

Stylesheet: FGDC ESRI

Name: greve_whole_points
Type: File Geodatabase Feature Class

Figure A-8. Multipoint Feature Class inside the Feature Dataset

Step 4: Create Terrain. Make an empty terrain feature class inside the geodatabase. In ArcGIS, go to ArcToolbox → 3D Analyst Tools → Terrain → Create Terrain.



Create Terrain

Input Feature Dataset: C:\data\DHI internship\3 - Terrain Generation\file_gdbase_trial.gdb\greve_whole

Output Terrain: greve_terrain

Average Point Spacing:

Maximum Overview Size (optional): 50000

Config Keyword (optional):

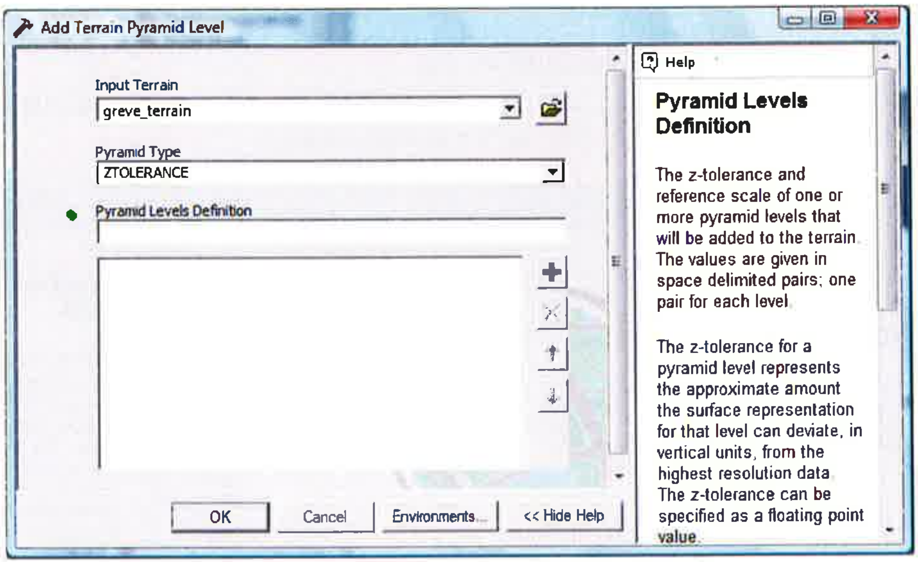
Help

Average Point Spacing

The average, or nominal, horizontal distance between points for the data being used to build the terrain. Data collected for photogrammetric, LIDAR, and SONAR surveys typically have a known spacing. This is the value that should be used. If you're unsure of the spacing you should go back and check the data rather than guess. The spacing is given in the horizontal units

Figure A-9. Create the terrain feature class

Step 5: Specify terrain pyramid levels. In ArcGIS, go to ArcToolbox → 3D Analyst Tools →Terrain → Add Terrain Pyramid Levels. Assign pyramid levels to the terrain feature class that you have created. A terrain dataset is a multi-resolution TIN. Terrain pyramid levels specify different resolutions of the display depending on the map scale you are using. By specifying pyramid levels, the display of the terrain as you work with it in ArcMAP is facilitated. Pyramids allow the reduction of points that will be used to visualize the surface. For each successive pyramid level, fewer measurements are used, and the vertical accuracy of the surface drops accordingly.



Input Terrain
greve_terrain

Pyramid Type
ZTOLERANCE

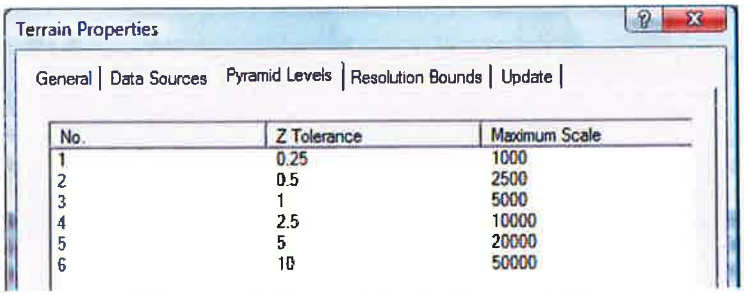
Pyramid Levels Definition

Pyramid Levels Definition

The z-tolerance and reference scale of one or more pyramid levels that will be added to the terrain. The values are given in space delimited pairs; one pair for each level.

The z-tolerance for a pyramid level represents the approximate amount the surface representation for that level can deviate, in vertical units, from the highest resolution data. The z-tolerance can be specified as a floating point value.

Figure A-10. Specify terrain pyramid levels



No.	Z Tolerance	Maximum Scale
1	0.25	1000
2	0.5	2500
3	1	5000
4	2.5	10000
5	5	20000
6	10	50000

Figure A-11. Pyramid levels of a created terrain

In this case, though, it is not critical to specify the pyramid levels. You just have to specify at least one or else the terrain class could not be built. This is because pyramid levels are essentially for visualization, and when the terrain is converted to raster in the succeeding steps, the full resolution (Pyramid level = 0) will be used.

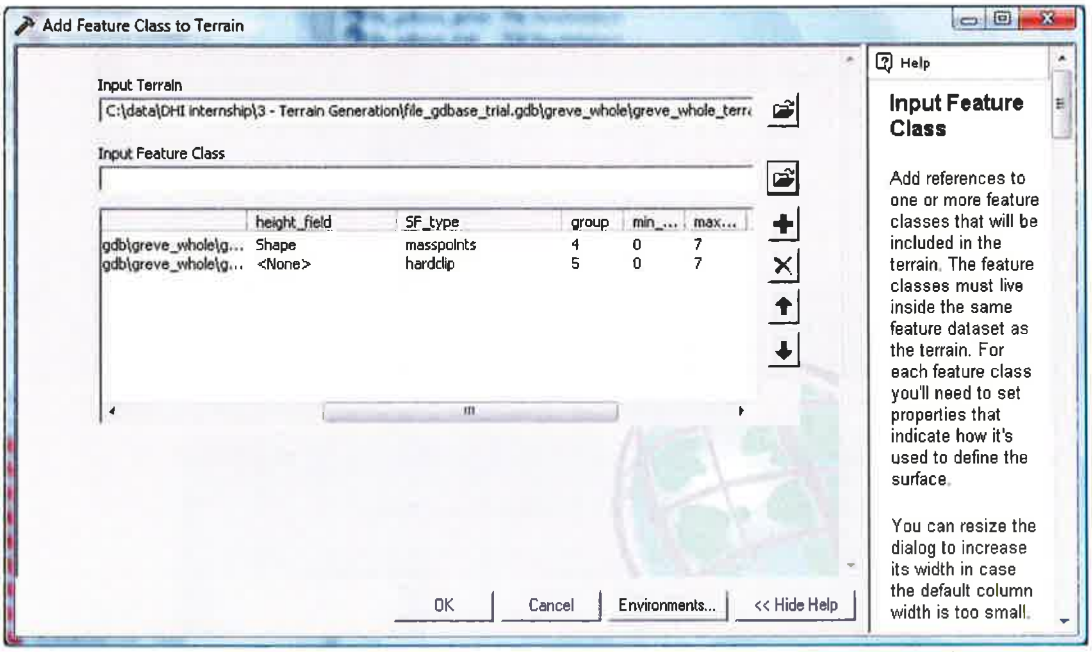
Step 6: Specify the feature classes in the geodatabase that will be used to build the terrain. This function is in ArcToolbox → 3D Analyst Tools →Terrain → Add Feature Class To Terrain.

The multipoint class containing point elevation data will be the basic feature used for building the terrain. The information about the elevation is contained in the "Shape" attribute of the multipoint class. For this example, the polygon feature class describing the boundary of the study area will be used as a hard clip feature, which will define the limits for where interpolation for the terrain will be performed.

Other features that may be used to build the terrain are:

- Breaklines. These are lines with height (z) recorded at each vertex. They become sequences of one or more triangle edges. Breaklines typically represent either natural features, such as ridgelines or streams, or built features, such as roadways.
- Erase polygons define holes in a terrain. These are used to represent areas for which you have no data or want no interpolation to occur.

- Replace polygons define areas of constant height. These are typically used to represent water bodies or man-made features that are flat.
- Hard and soft qualifiers for line and polygon feature types are used to indicate whether a distinct break in slope occurs on the surface at their location.



Input Terrain
C:\data\DHI internship\3 - Terrain Generation\file_gdbase_trial.gdb\greve_whole\greve_whole_terr

Input Feature Class

	height_field	SF_type	group	min_...	max...
gdb\greve_whole\g...	Shape	masspoints	4	0	7
gdb\greve_whole\g...	<None>	hardclip	5	0	7

Input Feature Class

Add references to one or more feature classes that will be included in the terrain. The feature classes must live inside the same feature dataset as the terrain. For each feature class you'll need to set properties that indicate how it's used to define the surface.

You can resize the dialog to increase its width in case the default column width is too small.

Figure A-12. Add the feature classes that will be used to build your terrain

Step 7: Build the terrain. In ArcToolbox go to 3D Analyst Tools →Terrain → Build Terrain, and a TIN-based surface will be generated. It took about 1 hr to build the terrain with the masspoints and clipping boundary polygon used in this exercise.

Input Terrain
D:\nina\DHI\Greve2.mdb\Greve2\greve_terrain

Build Terrain

Performs the necessary steps to make a terrain usable after its initially defined. It's also used to bring a terrain up to date after it's been modified.

Figure A-13. Build the terrain

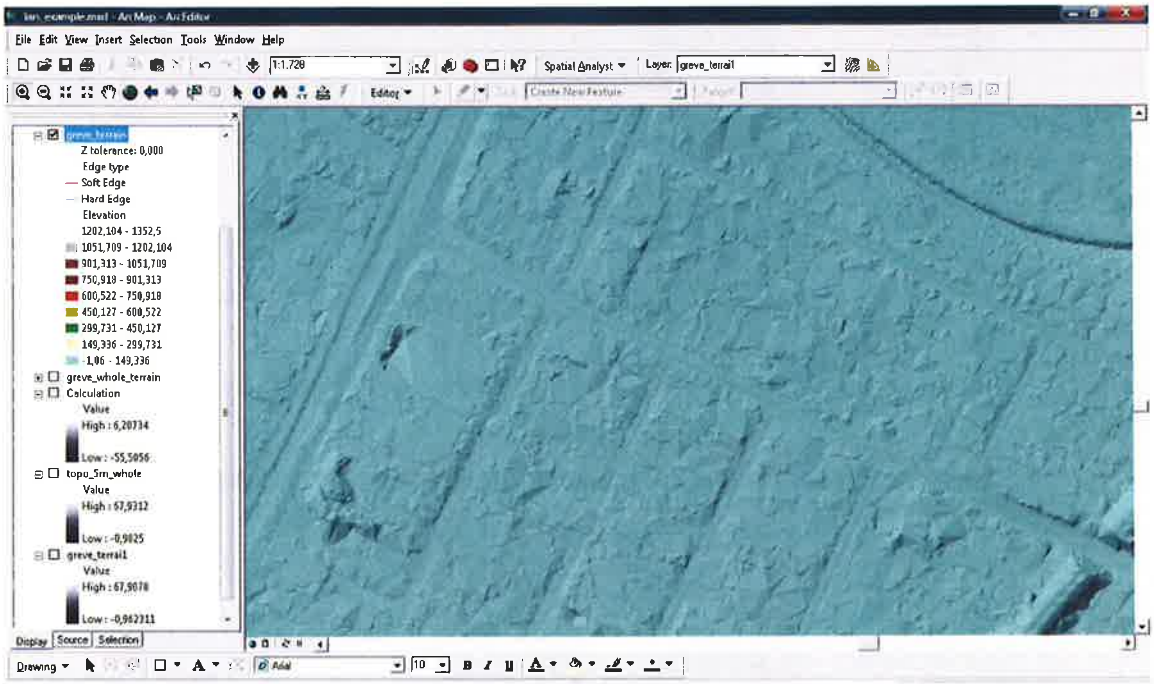


Figure A-14. Built terrain in ArcMAP

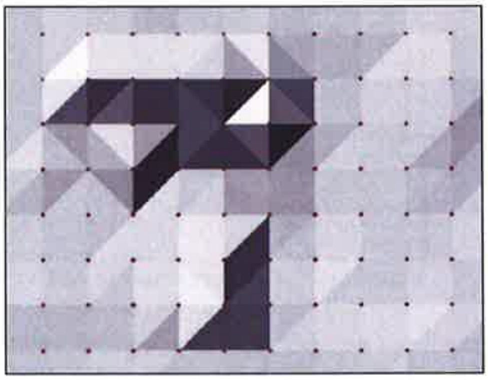
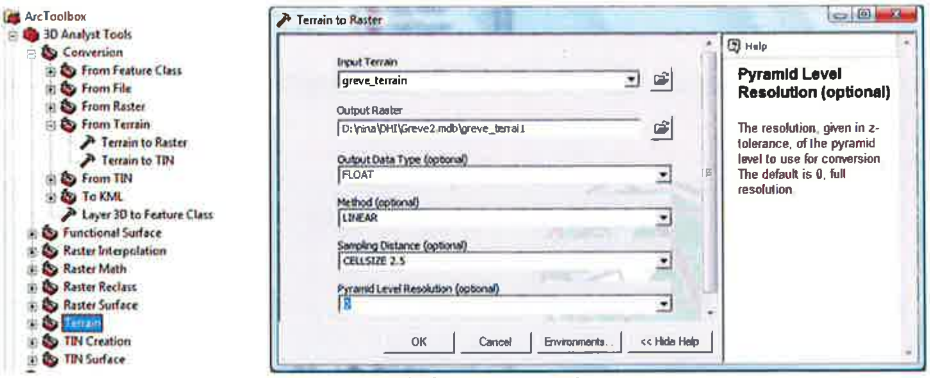


Figure A-15. Closer view of TIN-based terrain surface

Step 8: Convert terrain surface to raster. In ArcToolbox go to Conversion → From Terrain → Terrain to Raster. Remember that:

- Output data type must be Float (to avoid truncation of the elevations into whole numbers).
- The sampling distance must be set to Cellsize, and then specify the cellsize for the raster that you want.
- Specify 0 pyramid level resolution for full resolution.



Input Terrain: greve_terrain

Output Raster: D:\nina\DHI\Greve2.mdb\greve_terrai1

Output Data Type (optional): FLOAT

Method (optional): LINEAR

Sampling Distance (optional): CELLSIZE 2.5

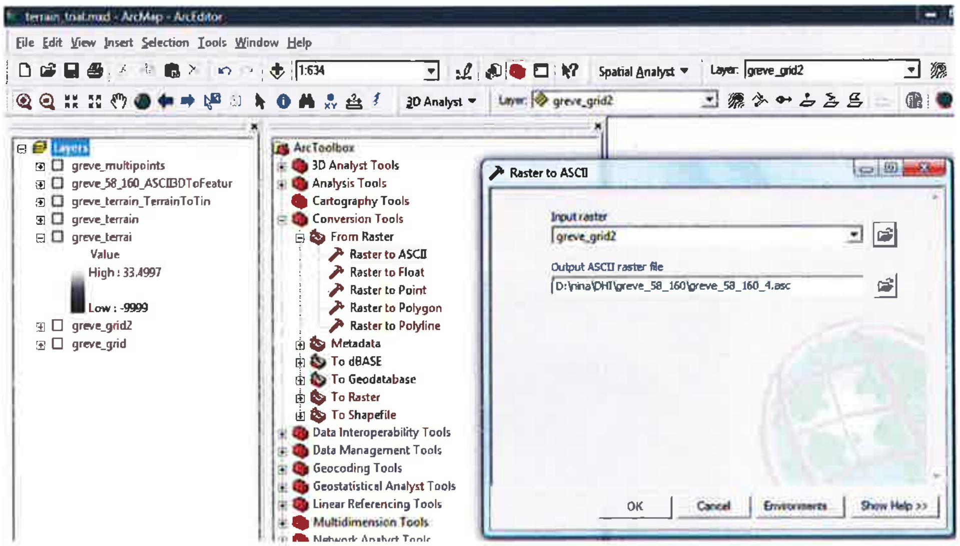
Pyramid Level Resolution (optional): 0

Pyramid Level Resolution (optional)

The resolution, given in z-tolerance, of the pyramid level to use for conversion The default is 0, full resolution

Figure A-16. Convert terrain to raster

Step 9: Convert raster to ASCII. Go to Conversion Tools → From Raster → Raster to ASCII.

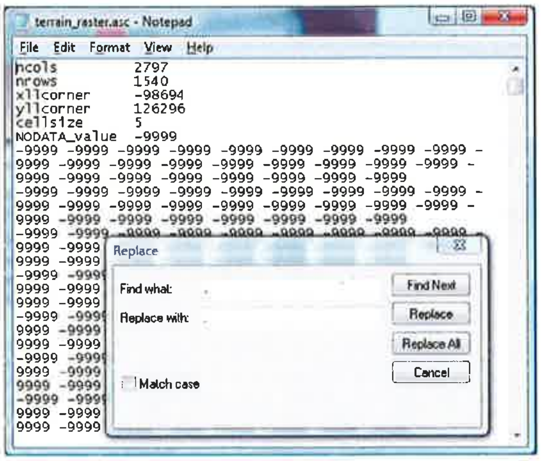


Input raster: greve_grid2

Output ASCII raster file: D:\nina\DHI\greve_58_160\greve_58_160_4.asc

Figure A-17. Convert raster to ASCII

Step 10: Make a Mike grid from the ASCII file using the Mike Zero Toolbox. Go to GIS → Grid to Mike. Make sure that the decimals in the ASCII file are in the right format (dots instead of commas).



```
ncols         2797
nrows         1540
xllcorner     -98694
yllcorner     126296
cellsize      5
NODATA_value  -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -
9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -
9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -
9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -
9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999
9999 -9999
9999 -9999
-9999 -999
9999 -9999
9999 -9999
-9999 -999
9999 -9999
9999 -9999
-9999 -999
9999 -9999
9999 -9999
-9999 -999
9999 -9999
9999 -9999
```

Find what: ,

Replace with: .

Figure A-18. Decimals in ASCII file must be points and not commas

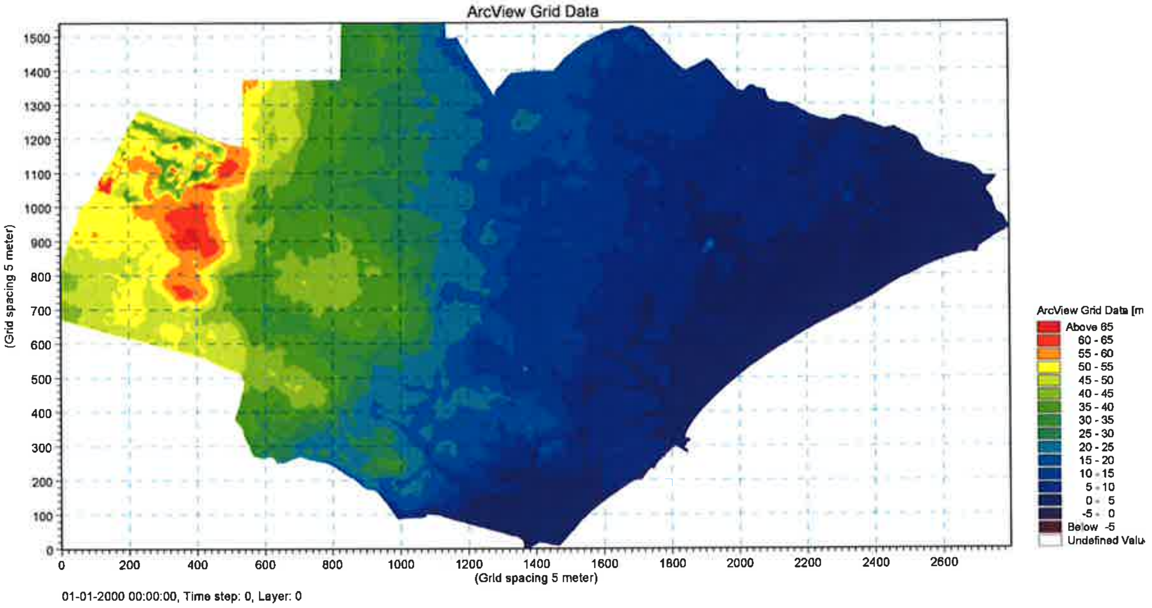


Figure A-19. Topography dfs2 file from terrain dataset

Step 11: Adding more feature classes to define the terrain. More details about the topography could be added to build the terrain. Available 3D shapefiles for buildings may be included in order to reflect the buildings in the terrain surface. Adding details to build the terrain will eliminate the subsequent steps of adding/subtracting rasters of surface features from the basic topography raster.

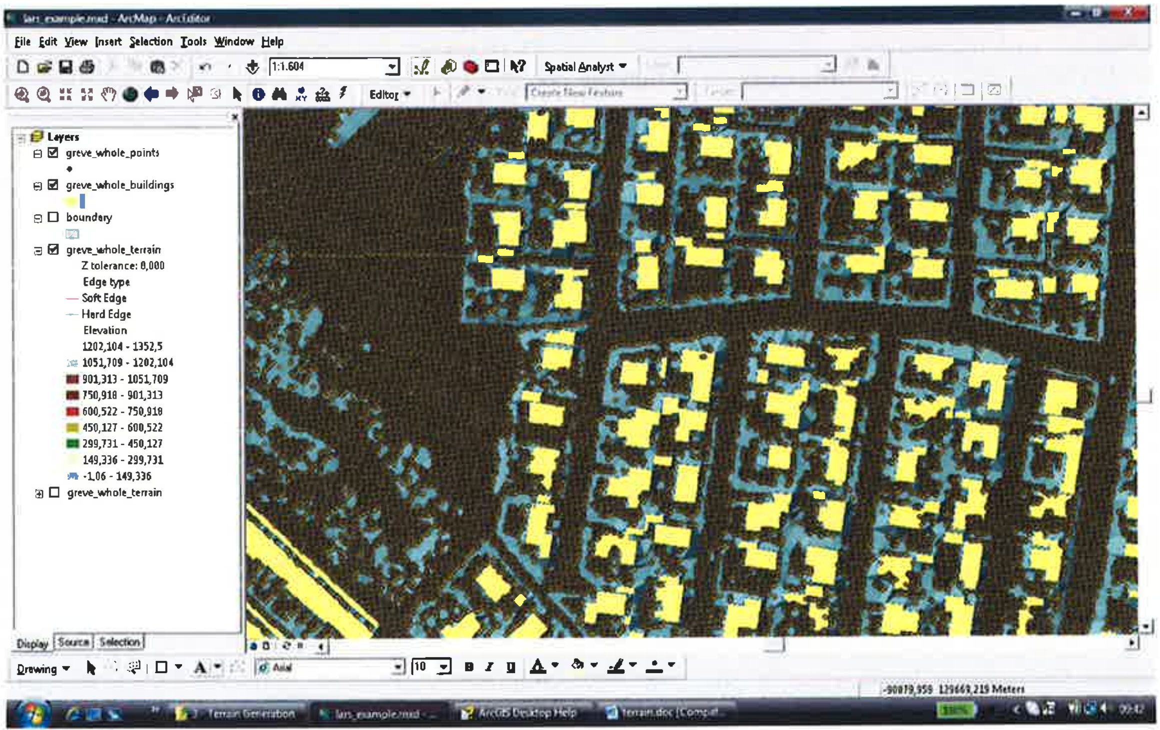


Figure A-20. **3D building shapefiles may be included in building the terrain**

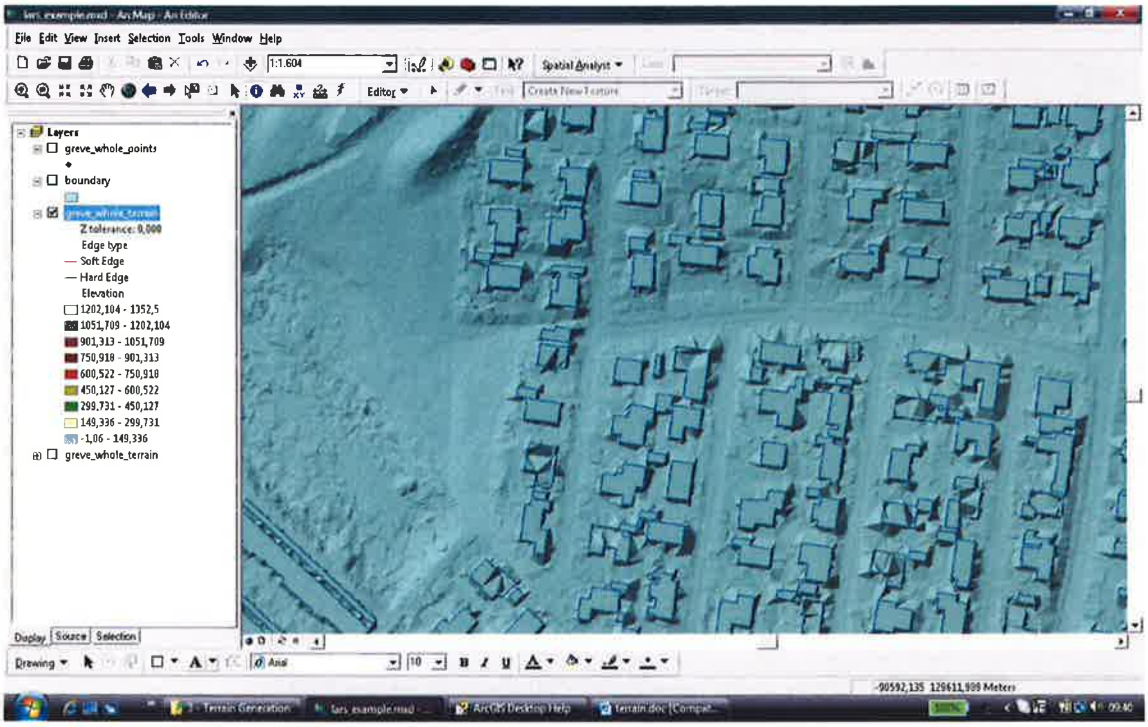


Figure A-21. **Terrain built with the buildings included as hard breaklines**

A.2. Adding Structures with Correct Heights to the DTM

The objective is to generate a surface that shows features significantly influencing runoff movement, including houses and buildings, and showing the true heights of the buildings.

Step 1: Prepare data. The common data that are available for this task include:

- DTM points: contain information about the ground surface including roads but excluding structures and features such as trees and bushes
- DSM points: contain information about features—structures, bushes, trees, etc.

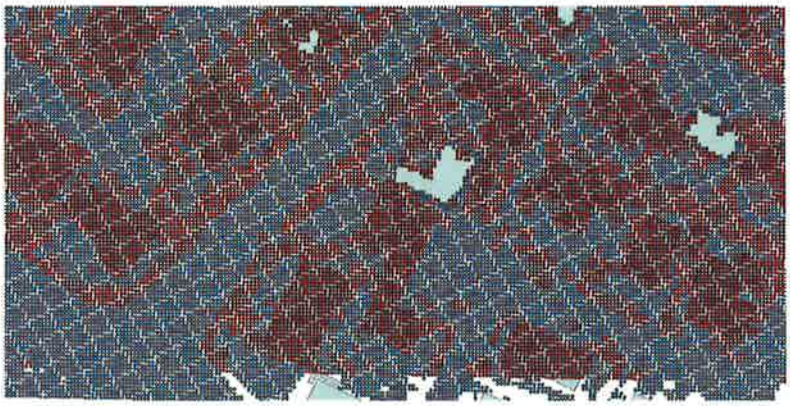


Figure A-22. DTM points (green) and DSM points (red)

These two sets of data cannot be just combined and used together to generate the DTM with buildings because, then, other features such as bushes and trees, would be included. We would like to consider just the "impervious" features.

In order to do this, the point information for the buildings must first be extracted. This can be done using the available polygon shapefile for the buildings. Select only the DSM points that correspond to where the buildings are located.

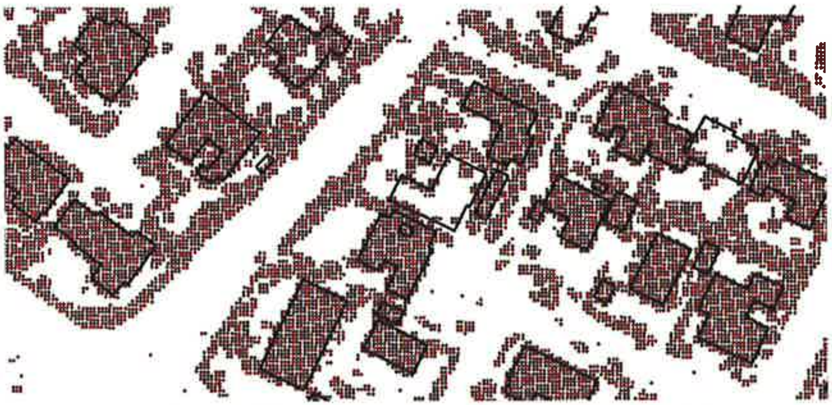


Figure A-23. Building shapefile over the DSM points

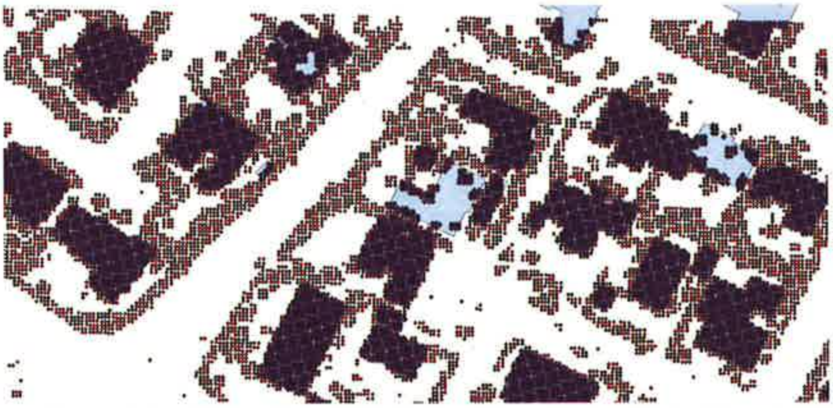


Figure A-24. DSM points selected when intersecting with building shapes

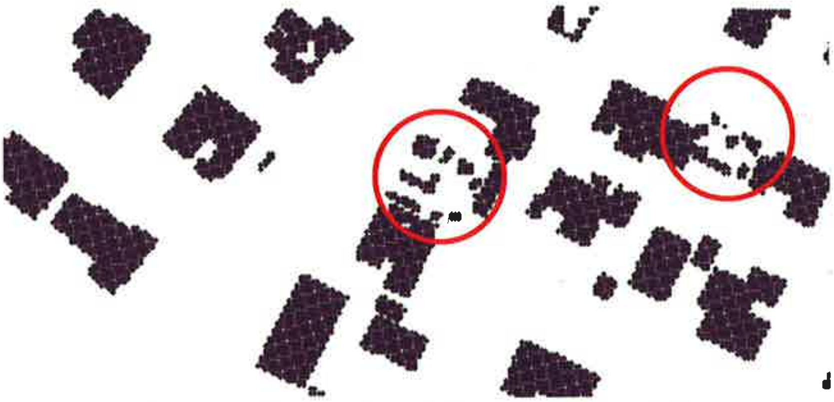


Figure A-25. Extracted DSM points for the buildings.
Note that there are sometimes no DSM points corresponding to some buildings.

Step 2: Generate "buildings" raster. A raster surface may then be generated with the selected "building points." This can be done through IDW interpolation or direct conversion of the points to raster.

For IDW interpolation, a more accurate method would be to interpolate only in the regions where there are points or inside the building shapes. (This may be achieved by using barrier polylines for the interpolation. However, an attempt to perform this was unsuccessful as the program crashed every time.) A raster may be interpolated by IDW method using the available points, and then the cells over the buildings can be extracted my mask. But then values will be interpolated in areas between the buildings, and this may distort the building edges.

Converting the points directly into raster may be a more accurate method to represent the buildings, but then, since there may be some points missing over some of the structures, doing this will generate partial or incomplete buildings.

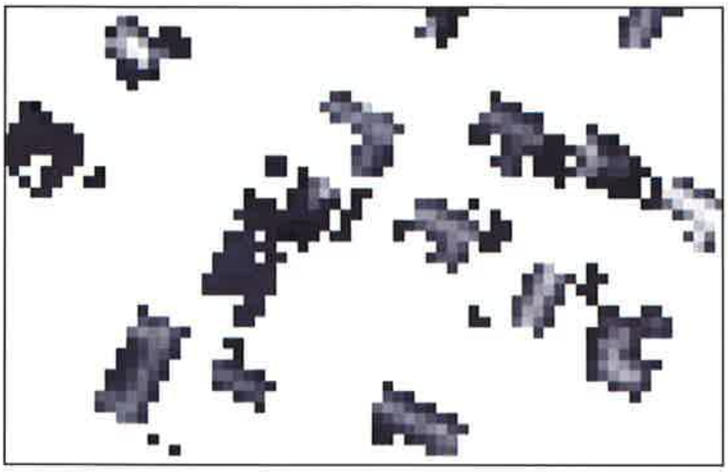


Figure A-26. The house/buildings raster

Step 3: Generate a "buildings raster" showing the correct heights of the buildings. The house/buildings raster will include the elevation of the ground. Another raster should be generated from the DTM points showing the land surface, but this DTM raster cannot be directly added to the house raster because the house raster includes the ground elevation. A raster having the values of just the house heights should be generated, and this is achieved by subtracting the DTM raster from the house raster. A raster having information on just the house heights is obtained.

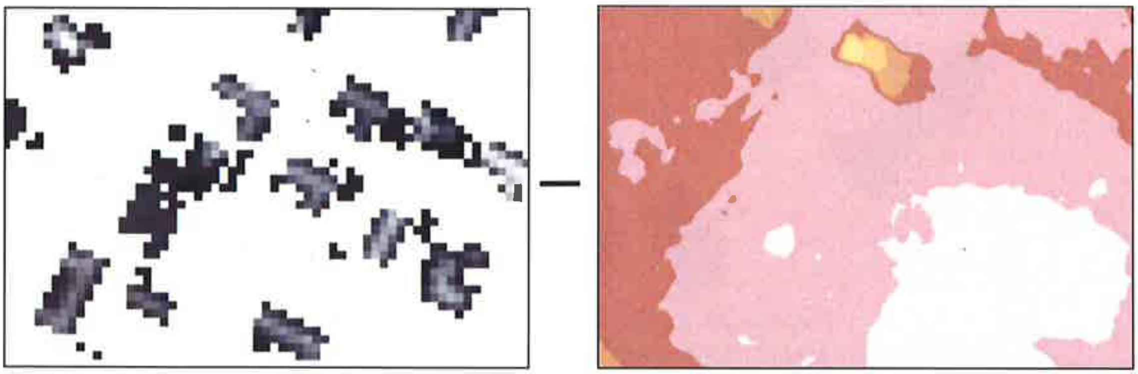


Figure A-27. Subtract the DTM raster(right) from the house raster (left)

Step 4: Add the "building/house heights raster" to the DTM raster to generate a DTM reflecting correct building heights. Before the "house/building heights raster" generated in Step 3 can be added to the DTM raster, the spaces between the houses need to be assigned values (for raster calculator to work properly), and this is achieved through reclassification of the raster.

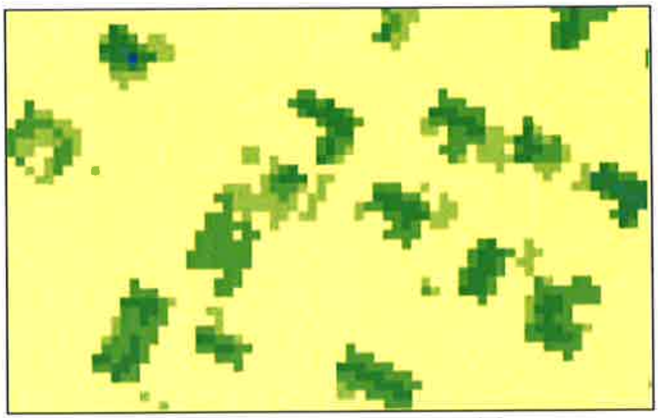


Figure A-28. Reclassified house heights raster (Value of 0 assigned for spaces between the houses)

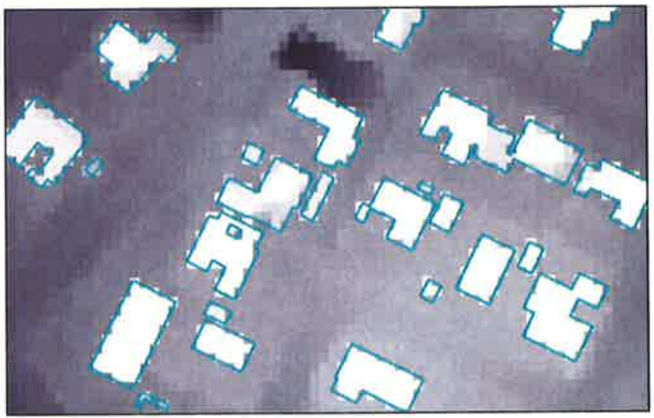


Figure A-29. The final raster showing land surface and actual house heights

Step 5: Convert the final raster showing the terrain and buildings with correct heights into Mike grid. The final raster can be converted to ASCII, and then to a Mike grid using the Mike Zero Toolbox.

Figure A-30. Mike topography grid with buildings and houses with "actual" heights