Examensarbete

TVVR 12/5010

Urban Flooding in Gothenburg - A MIKE 21 Study

Master of Science Thesis in Department of Water Resources Engineering

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Acknowledgements

I would like to thank my supervisor Arun Rana who helped me with setting up the model, taught me how to use MIKE 21 and answered my questions throughout the project. I would also like to thank Sten Blomgren from DHI for providing me with the license for DHI MIKE21 and with technical support and Roger Groth from the GIS center at Lund University for the license for ArcGIS 10. I would also like to acknowledge the city of Gothenburg from which I received the topography data and Claes Hernebring from DHI and Professor Lars Bengtsson for the rainfall data.

Abstract

Climate change has affected the extreme weather throughout the world. Studies have shown an increase of the extreme precipitation in Gothenburg, Sweden. At the same time, space limitations and cost considerations prevent the development of an optimized drainage system. Designing a stormwater system for an extreme rainfall is impossible due the high cost. In addition, the lack of space limits the availability of infiltration areas. However, the cost associated with floods in the cities is very high due to high property and infrastructure value and the high economical activity.

In this paper, a two dimensional (2-D) hydrodynamic simulation model using MIKE 21 was developed as a tool to simulate stormwater related flooding in the central part of Gothenburg. This was followed by development of flood risk maps. The model was developed by using topographical data and fine time resolution precipitation data. This was then used to simulate 2-D overland flow in the catchment to develop, implement and verify the model approach in urban areas. The topography data is first processed in ArcGIS so that it can be further used in MIKE 21.Then, a bathymetry for the area is created in MIKE 21 considering boundary layers and other parameters including land value. For the Manning number, two cases were considered: in the first case, a constant value of the Manning number was assumed over the entire computational grid and in the second case, a land use map was used with different Manning numbers for buildings, roads, parks and water. The model simulates unsteady flooding and drying processes over the urban areas.

The developed two-dimensional model shows that the parts of the study area including the canals, the streets and the space in between the residential buildings would be flooded if the drainage system is blocked due to extreme precipitation. The model results provide spatial flood risk information such as water depth and flow velocity during flooding and can be used to evaluate the effectiveness of flood protection practices in central Gothenburg. Flood maps with maximum water level have been generated and presented in the study. The findings from this model can be used for development of a comprehensive urban flood management plan of Gothenburg. The overall objective of the output from model is to provide an integrated planning and management tool to allow cost effective management for urban drainage systems.

Keywords: Gothenburg, two-dimensional hydrodynamic model, DHI MIKE 21, flood inundation maps

Abbreviations

AMSL: Above Mean Sea Level

ASCII : American Standard Code for Information Interchange

DEM : Digital Elevation Model

DTM: Digital Terrain Model

EU: European Union

FEMA: Federal Emergency Management Agency

LiDAR: Light Detecting and Ranging

MSB: Myndigheten för samhällsskydd och beredskap (Swedish Civil Contingencies Agency)

SGU: Sveriges geologiska undersökning (Geological Survey of Sweden)

SMHI: Sveriges meteorologiska och hydrologiska institut (Swedish Meteorological and Hydrological Institute)

1D: one-dimensional

2D: two-dimensional

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Introduction

Flooding, as defined by the EU Floods Directive (Directive 2007/60/EC), occurs when land that is not normally covered by water becomes temporarily submerged in water. Flooding is a major problem across the world because of the high number of fatalities and the enormous amount of economic damage that this natural disaster causes. Between 1980 and 2008, 2 887 flood events have occurred, 195 843 people have been killed and the economic damage was over US $397 billion (PreventionWeb, 2011). Sweden has less destructive floods but flooding is still a problem for some cities like Karlstad, Gothenburg and Mariestad. Similarly to other cities in Sweden, flooding frequency in Gothenburg has been increasing in recent years (MSB, 2011). For example, in Gothenburg, there were floods almost every year in the last ten years. Located on the Göta River delta, the city of Gothenburg is at risk of flooding from the Göta river, the sea and overload of the sewer system. A flood was caused by extreme sea levels in 2005, the Mölndalsån river and other tributaries of Göta river were flooded in 2006 and 2008 and, in 2010, flash floods due to heavy rainfall caused flooding of several basements (Moback et al., 2011). Recently, in 2011, the traffic was stopped on August 14 on Dag Hammerskölsleden due to flooding (Sydvik, 2011). Another flood in 2011 occurred on December 10 in the areas of Stampen, Norra Gårda, Göta tunnel, Marieholm and Säveån. The floods resulted in closure of roads and flooding of some basements. (Johansson & Wettergren, 2011) .

Objective

The purpose of this study is to develop flood risk maps of the Central part of Gothenburg by using DHI MIKE 21, topography and the precipitation. By using data for three precipitation events, the water level and flood velocity in the area are determined. These flood risk maps can be further used in city planning for the analysis of the flood management practices. Although Gothenburg has parts of a flood management plan, the city still does not have a comprehensive plan (Augustsson, 2010). Identifying the areas of Gothenburg that are going to be flooded if the drainage system is overloaded by extreme precipitation events should be a consideration when developing the flooding management plan which is an important flood protection measure.

Study Limitations

The proximity of Gothenburg to the Göta River and the North Sea and the possibility of extreme precipitation are factors that increase the risk of flooding. In this study only flooding due to high amount of precipitation is considered. Furthermore, it is assumed that due to the high amount of rainfall, the drainage system is blocked and is excluded from the model. The water level and velocity in Göta river and the two canals Rosenlund and Stora Hamn could not be accurately analyzed because no hydrograph data was available and also because one-dimensional flow is better simulated in MIKE11. Due to the unavailability of data (the tidal variations, river cross-sections and river bathymetry and drainage system) and the small scope of the study, the model was simplified to include only the topography of the area and precipitation.

Literature Review

Gothenburg, with a population of over half a million people and an area of 721.64 km^2, of which 271.41 is water, is the second largest city in Sweden (Moback, 2011). There are 70 lakes and 15 watercourses in the city (Stadsbyggnadskontoret, 2003). The city is located in south-western Sweden in Västra Götaland, on the delta of Göta River which discharges into the North Sea. The city was built by Dutch planners in 1621 on a marshy area as an orthogonal grid. There were an abundance of canals and fortifications which made the city resemble Amsterdam (Gunilla, 2010). Gothenburg was built in a swamp in the lowest area of Göta River in order to protect the city against attacks from Denmark and Norway and, as further protection; fortifications were placed on the hills (Moback, 2011). The location was also chosen so that the city can be a port with access to the West (Göteborgs Stad, 2009). Some of the fortresses have been destroyed but most of the canals remain today. From the second half of the 1800s, the city has been expanding into the valley along the Göta River (Ekfeldt, 2007). Figure 1 shows the location of Gothenburg in Sweden.

Figure 1 Location of Gothenburg (Google Earth 2012)

Nowadays, the city is a major industrial and cultural center in Sweden and Northern Europe. Gothenburg is the largest port in Scandinavia and its major exports are cars -Volvo, ball bearings and paper (*Encyclopædia Britannica* 2012)

Extreme Weather Events

The worst storms in Gothenburg since 1900 occurred in 1902, 1969 and 2005 (Lindahl et al., 2006). The storm in 2005, "Gudrun," had wind speeds of 40 m/s and the sea level at Torshamnen reached 11.44 m which is 1.48 m AMSL (Lindahl et al., 2006). At another event at Lärjeholm, the sea level was even higher than the maximum level that could be measured, at over 11.98m (Lindahl et al., 2006). The biggest snow storm was in 1995 and the snow depth at Säve was 52 cm. The biggest ice storm was in 1921 and caused major electricity problems (Lindahl et al., 2006). The maximum monthly rainfall was measured at Säve and was 220mm. The highest amount of rainfall in Gothenburg occurred in 1997 between August 26 and 27 and reached 117.2 mm (Lindahl et al., 2006). In Orust in 2002, the official measurement was 80mm but unofficially the rainfall was between 180-200mm (Lindahl et al., 2006). Extreme rainfall also occurred in 1939 when on July 17, 128 mm was measured at Väderöbod (Lindahl et al., 2006). These extreme events are summarized in Table 1.

Table 1 Extreme Events in Gothenburg (Göteborgs Stad, 2009).

Weather Conditions	Station	Max Record Level
Precipitation		
Month	Säve	220 mm
Day	Gbg-Stad	117.2 mm
Hour	Gbg-Stad	29.1 mm
Snow Depth	Säve	52 cm
Maximum Temperature	Säve	+34.1 ^{0}C
Max Temperature of Göta River	Lärjeholm	+24^{0}C
Minimum Temperature	Säve	-26.4^{0}C
Wind Speed	Vinga	36 m/s
	Trubaduren	Gust 40.1 m/s

Climate Change and Frequency Analysis

Climate change data was estimated by using the regional atmospheric oceanographic model from the Rossby Center (Lindahl et al., 2006). The model was also used to interpret the results from global models from the Max Planck Institute for Meteorology in Germany and Hadley Center in the UK (Lindahl et al., 2006). The calculations were based on different green house gas scenarios by IPCC. In Gothenburg, the temperature is going to increase by 3- 4 ^{0}C and it is expected that the rainfall will increase in the spring, fall and winter and decrease in the summer (fig 2). The extreme rainfall is expected to increase for all seasons. The sea level is expected to rise between 0.1 m to 0.9m (Lindahl et al., 2006). The changes in climate are epected to occur by 2100.

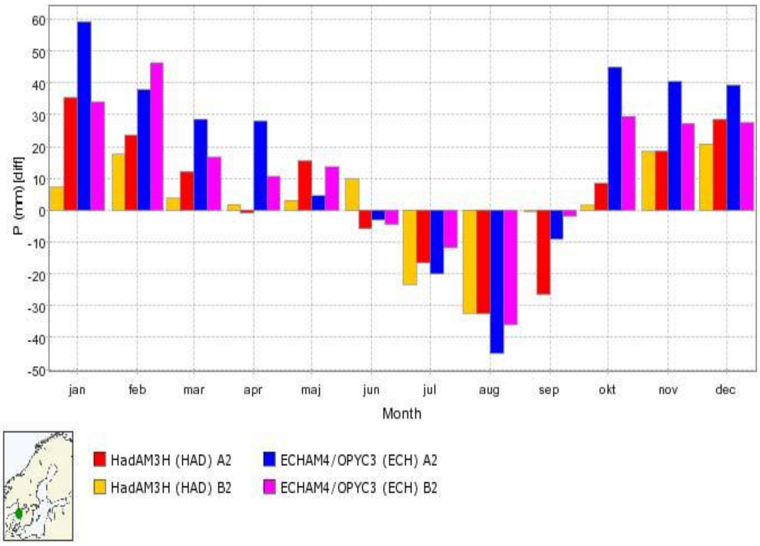

Figure 2 Change in Precipitation due to climate change (Lindahl et al., 2006)

According to SMHI study: **"**Klimatunderlag för sårbarhetsanalys Göteborgs Stad," there is a trend of increased precipitation and discharge in the rivers in the last 50 years. The reasons are: change in land use such as deforestation, more impervious surfaces, urbanization, hydropower and climate change. Hydropower regulates the water flow and the extreme high rainfall events are smoothed. As a result, the flood events become rarer but when they occur their magnitude is higher and they are more unpredictable.

According to SMHI, the return period for the extreme high water level, which corresponds to 12.9 m, to be exceeded by a single storm event is 1000 years at Rosenlund. The return period for planning is 100 years which corresponds to mean sea level of 12.3m.

Return periods are calculated based on frequency analysis of the previous years. A return period means that the value is reached or exceeded once in the period. So, the probability of 100 year flood each year is 0.01. But the probability of 100 year flood to occur in 100 years is 63 % (Göteborgs Stad, 2009). Analysis of the rainfall data collected between 1961- 2005 shows that for one day precipitation event, the value for 100 year return period is between 67-97mm (Lindahl et al., 2006). The maximum precipitation measured of 117.2 mm had a return period of 200 years (Göteborgs Stad, 2009).

Previous Studies

Flood Hazard Maps have been prepared for Gothenburg by MSB in order to be used for the first phase of the EU Flood Directive (Directive 2007/60/EC), the Preliminary Assessment of areas with risk of flooding. In this first phase, the flood hazard maps have been prepared only for flooding from lakes and rivers for the maximum flow that can occur and for 100-year flood. Areas with significant flood hazard have been determined with respect to economic activity, environment, health and heritage. One of the areas is Gothenburg. Coastal flooding was not considered because the elevation database needs to be updated. In the area of Gothenburg with the highest estimated flow, 6 767 people live and 37 657 work (MSB, 2011). In the next phase of the EU Flood Directive, the local county boards (Länsstyrelse) have to develop flood risk maps and then, based on these maps, a flood management plan has to be prepared (MSB, 2011).

Another study for flood mapping was done for Stora Ån by DHI. The watercourse Stora Ån in Gothenburg receives the most stormwater compared to its size. The study was done for 100-year flood in combination with high sea level and the purpose was to see if more stormwater can be discharged due to a new housing development. The value of the 100-year flood near Välen was estimated to be 7.5m^3/s. The catchment area at this place was 2208 ha (DHI, 2009). The analysis was done for M=10, 18 and 30. The study showed that in all three cases, the only major road flooded would be Abyvägen. To increase the capacity of the watercourse, there are also a number of small ponds.

Flood mapping in Gothenburg was also done as a part of a project **"**Plan B – dealing with floods in densely populated cities with extreme rain" (Plan B – hantering av översvämningar i tätorter vid extrema regn) that has been carried out by DHI Sweden in cooperation with the some municipalities in order to develop a methodology for analysis of urban flooding due to extreme rainfall. The analysis was used to provide information for water planning which includes measures to minimize the consequences of flooding, lead the stormwater to a storage place and provide alternative routes for the stormwater. The project used MIKE Flood Urban to model the sewer system and the overland flow. The current system was evaluated for 10 –year and 100-year flood. In Gothenburg, a basin in the central part was chosen with an area of 530 ha. The results show that the capacity for the 10-year flood is good and only a few places are flooded. The 100-year flood results in significant flooding. Flooding occurred most in the streets of Haga, Långgator and Linnegatan near Vegagatan. In the next part of the study, a list of actions was developed to reduce the flood such as to lead the flow to secondary paths and delay the flow. The measures depend on the area, the level of flood protection that is needed and feasibility. Two plan B actions were modeled: a ditch, with an area of 5000 m^2 and depth of 0.5m between Vegagatan and the Natural History Museum, and a barrier on the Fjärde Långgatan and Linnegatan. The actions reduced the flood area. Although the actions have major effect locally, their overall effect is not much.

In 2010, a National Platform for dealing with natural disasters held a series of seminars related to the adaptation of the Swedish cities to climate change. In the future, it is expected that climate change would lead to much more extreme weather events such as floods, snow or hurricanes. The seminars involved the following agencies: Planning, National Food Administration, MSB, Environmental Protection Agency, SMHI, National Geotechnical Institute and SGU. The purpose of these seminars was to give the agencies examples of the work that has been done and to facilitate networking. The title of the publication is: Dealing with Flood Problems-Inspired Examples (Att hantera Översvämningsproblematik – inspirerande exempel). One of the examples was Gothenburg discussed by Ulf Moback in Adaptation of Gothenburg to Climate Change (Anpassning av Göteborg till förändrat klimat) . According to the seminar, the risk for extreme weather events in Gothenburg is increasing because of the global warming. The highest risk is the increase in temperature which would lead to increase in the mean sea level. An increase in sea level of around 1m and a storm like Gudrun would cause extreme damage to the buildings and infrastructure and most of the central Gothenburg would be under water. To adapt the city to the rising sea level, there was a project "Water City" between 1999 and 2002. In 2003, the city council developed a master plan for water which states that the margin of safety for building permits has to be 1m above extreme high tide level. The city was divided in three zones: coastal zone in which new constructions have to build 1.5 m above the mean sea level, central city part- 1.8m and Norr Marieholmsbron -2m. To this value, an additional 1 m for safety margin is added and 2m - for important public buildings. In addition, from 2004 the city

planning is investigating what the risk in Gothenburg is with respect to extreme weather and climate change and what can be done to protect the city from these events.
In addition to increase in the mean sea level, another problem would be the increase in rainfall. An increase in rainfall would also cause problems mostly because the flow of the river would increase which can cause flooding, erosion and landslides. Also, the stormwater system would not be able to handle the increased flow. At the same time, there is increased demand for housing and office buildings in the central part of the city which lies at the lowest level.

Recently, there has been an investigation of the city preparedness for extreme weather and climate change with respect to water, electricity, transportation, etc and the findings are summarized in the report by Göteborgs Stad in Extrema Väderhändelser (Extreme Weather Occurences). In case of flooding, there would be damage to the fiber optic internet and the electricity supply and the repair costs would be high. Prolonged rainfall, high water levels and increase in water temperatures would cause problems for the water supply. A combination of rainfall, high sea level and freezing of the soil can be a problem for the sewer system and can cause flooding of basements and sewer overflows. Landfills have to be secured for leaching of contaminants due to the raise in water level and flooding. The transportation system can also be damaged. High tide level and high rainfall would cause the streets to become flooded when the sewer system does not work. At theoretical maximum level of 12.7m or 2.74 m AMSL, twenty percent of Gothenburg streets and sidewalks would be flooded (Göteborgs Stad, 2009). The risk of extreme weather events in Gothenburg is defined based on the return period and the effect on the utilities and the infrastructure that can be damaged such as: water, electricity, etc (Göteborgs Stad, 2009). The city preparedness to flooding can be improved by better cooperation and coordination between the organizations. For example, the city council has formed a group which involves companies in infrastructure that could cooperate if there is an extreme event (Göteborgs Stad, 2009).

According to the Stormwater Handbook, *Dagvatten, så här gör vi!*, published by Gothenburg, a preliminary investigation is needed for the comprehensive planning of stormwater. The preliminary investigation requires geological and hydrological studies which involve: determining the infiltration capacity of the soil, data for the groundwater levels and groundwater flow with recharge and discharge areas, the distribution of precipitation on the catchment and the level of pollution of the stormwater (Göteborgs Stad, 2010). There should be also investigation of the capacity of the existing stormwater system and the areas that are upstream from where water can flow (Göteborgs Stad, 2010). The areas which are confined and where the collected water can cause damage have to be avoided. According to the EN standard 752, the stormwater system has to be designed for 10- to 50-year flood frequency. Surcharges when water in the stormwater system is in pressure can cause flooding in basement due to the backwater effect if there is not a valve (Schmitt et al., 2004). Therefore, surcharge needs also to be used for the design.

Flood Models

Urban development increases the amount of runoff because there are more impervious surfaces compared to rural areas. The result of the urban development is larger flow and reduced time of concentration. The extent and severity of urban flooding is influenced by the local hydrology, soil type, the amount of impervious surfaces and the stormwater network capacity (Bishop &

Catalano, 2001) **.**The cost associated with flooding depends on the physical aspect of the flood such as duration, water level and amount of water that exceeds the capacity of the sewer system (WeiFeng et al., 2009). The generation of surface overland flow is altered due to human activities and the urban hydrological processes become very complex. One of the reasons is that urban areas are very heterogeneous with respect to land use and also the complexity is due to the drainage systems. There is interaction between surface water and groundwater and between groundwater and the sewer system. The problems in urban flooding result because the cost of constructing sewer systems for the most extreme conditions is too expensive (WeiFeng et al., 2009). In a study of the Beijing Olympic Village, Weifeng showed a conceptual model developed for flood studies in urban areas. First, a rainfall-runoff model was used for paved and unpaved areas. The computed runoff is input in the 1D model, which represents the sewer network system, and then the two dimensional overland flow is modeled. The integration between the models is accomplished by using the computed runoff as boundary condition for the 1D model (WeiFeng et al., 2009). Another important parameter is the roughness which usually is represented as a matrix of values that corresponds to the DTM (Bishop & Catalano, 2001)**.**

Flood maps represent the probable height of water and extent of area that would be inundated during a simulated event. Flood Plain Hazard Maps determine which areas are at risk of flooding and are used to evaluate the possible locations of the structural controls. The Flood Hazard Maps are usually constructed for different return periods usually 20-, 50- or 100-year floods (OPDEM, 2011). The properties of a flow field are described in three dimensions. For some cases, there is almost no change in one of the direction so only two dimensions are needed. In conduits or in natural watercourses, flow can be described in only one dimension and it is assumed that the velocity is constant at the cross-section because only the change along the conduit with length is needed. The natural watercourses are never one-dimensional but the simplification is possible because it gives close approximation. Therefore, the flow can be calculated by using one – or two- dimensional approach. One-dimensional models assume that the velocity varies only in longitudinal direction. At each cross-section the velocity is averaged over both depth and width of the channel and a single water surface elevation value is calculated (FEMA, 2009). An essential input in one-dimensional models is the flowpath which must be given in advance (WeiFeng et al., 2009). So, to give accurate results, 1D models have to be overlaid on DEM. The results can be inaccurate, especially in urban areas because there, roads or structures can create preferential flow paths (FEMA, 2009). Another disadvantage of the one dimensional models is that these hydraulic models assume steady-state conditions. However, in urban areas the storm events are not long enough to result in steady-state conditions. The one-dimensional models do not consider catchment storage and average velocity are taken at the cross-sections which means that peak velocities would be underestimated (Bishop & Catalano, 2001).

In 2D models velocity is only averaged over depth. The two-dimensional models calculate the surface water elevation with more accurate resolution and determine the floodplain extent directly (FEMA, 2009). A disadvantage of the two-dimensional models is that they require smooth bathymetry so a very large number of cells is required to represent channels and they, unlike one-dimensional models, cannot describe control structures such as pumps. In addition, GIS is integrated with the hydrodynamic models. An integrated one- and two-dimensional model is a way to eliminate some of these disadvantages. However, there are still some issues with these models. The topography, DTM (model which represents bare earth with trees and buildings removed) should have a resolution that needs to correspond to the smallest change in elevation that results from hydraulic structures such as embankments, flow channels and road inverts (Bishop & Catalano, 2001). The flow boundary conditions include more internal boundaries than in rural areas (Bishop & Catalano, 2001).

MIKE 21

MIKE 21 Hydrodynamic module is a two dimensional model which calculates the water depth variations. The model was developed initially for marine and coastal applications but now it is also commonly used in flood studies. The equations that MIKE 21 Hydrodynamic module uses are a form of the Saint Venant equations, as described in the MIKE 21 FLOW MODEL Hydrodynamic Module Scientific Documentation updated in 2011:

Mass Balance Equation:

$$\frac{\partial \xi}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t}$$

Conservation of Momentum Equation in x-direction:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \xi}{\partial x} + \frac{gp\sqrt{p^2+q^2}}{C^2.h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx}) + \frac{d}{dy}(h\tau_{xy}\right] - \Omega_q - fVV_x + \frac{h}{\rho_w}\frac{\partial}{\partial x}p_a = 0$$

Conservation of Momentum Equation in y-direction:

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + gh\frac{\partial \xi}{\partial y} + \frac{gq\sqrt{p^2+q^2}}{C^2.h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy}) + \frac{d}{dx}(h\tau_{xy}\right] + \Omega_p - fVV_y + \frac{h}{\rho_w}\frac{\partial}{\partial y}p_a = 0$$

Where:
h(x,y, t) – water depth =ξ-d, m
d(x,y,t) – time varying water depth , m
ξ(x,y,t) –surface elevation, m
p,q (x,y,t)- flux densities in x- and y-directions (m 3 /s/m) = (uh,vh);
(u,v) = depth averaged velocities in x- and y-directions
C(x,y)- Chezy resistance (m ½ /s)
g-acceleration due to gravity (m/s 2)
f(V)- wind friction factor
V, Vx, Vy (x,y, t)- wind speed and components in x- and y-directions (m/s)
Ω(x,y)- Coriolis parameter, latitude dependent (s -1)
Pa (x,y,t)- atmospheric pressure (kg/m/s 2)
Pw- density of water (kg/m 3)
x,y- space coordinates (m)
t- time (s)

$\tau xx, \tau xy, \tau yy$- components of effective shear stress

These equations are used to simulate unsteady two-dimensional flow in one layer for fluids which are vertically homogeneous (DHI, 2011). The computational grid which is used in MIKE21 is shown in Figure 3.

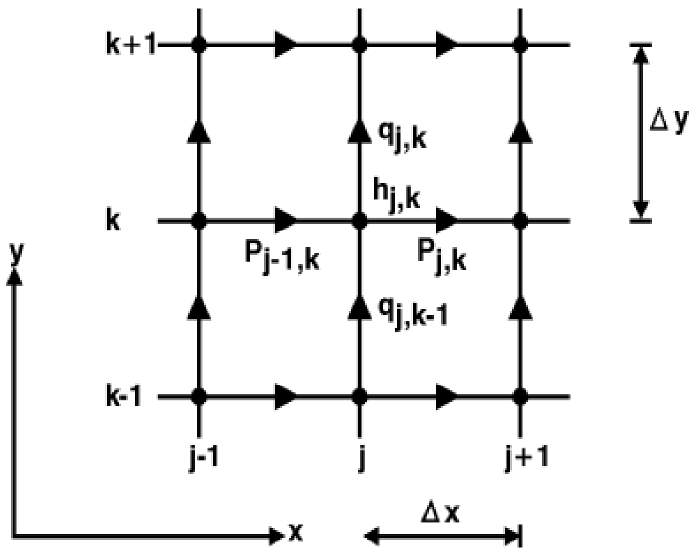

Figure 3 Computational Grid (DHI, 2011)

In MIKE 21 like in MIKE 1D, the Double Sweep Algorithm is used. The continuity and momentum equations are solved by alternating between the x and y direction (DHI, 2011). In the x- sweep , the equations are solved by using ζ from n to n+1/2 , p from n to n+1 and q from n-1/2 to n+1/2. In the y-sweep, the values for ζ are from n+1/2 to n+1 , p is from n to n+1 which was calculated in the x-sweep and q is from n+1/2 to n+3/2 (Figure 4)

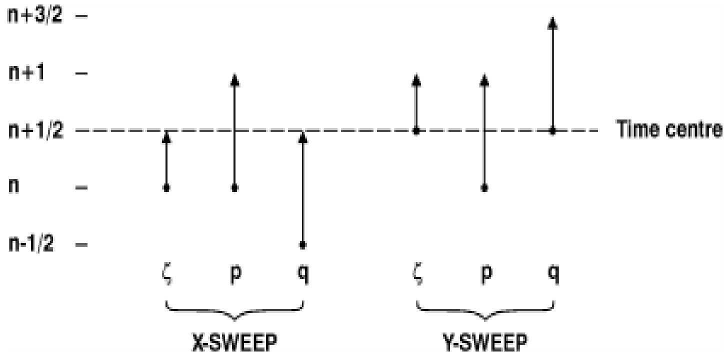

Figure 4 Double Sweep Algorithm (DHI 2011)

To avoid using iteration, MIKE 21 uses side feeding technique (DHI, 2011). So, the x-sweep solutions in the first step go in decreasing y-direction and in the next step in increasing y-direction.

Method

DHI MIKE21 was used to simulate three rainfall events in 2002, 2003 and 2010. Data was obtained through the city of Gothenburg and also from Claes Hernebring from DHI Sweden. The topographic data was first converted in ArcGIS to ASCII file that could be used in MIKE 21. A simulation in MIKE21 was used to determine the resulting water level and flood velocity during the three rainfall events.

Data Collection

Elevation Data

The topographic data used in the model was provided by the city of Gothenburg as an AutoCAD drawing (Figure 5a). The region is located in the Central part of Gothenburg (Figure 5b) and has an area of around 1.577 km^2 and coordinates between 57° 42.610'N and 11° 57.210' E to 57° 41.88'N to 11° 58.380'E.

Figure 5a Topographical Data in AutoCAD Figure 5 b Google Map View of the model area

The topographical data was converted to raster by using ArcGIS 10. First, the AutoCAD drawing of the area was imported into ArcGIS as point, polygon and polyline shapefiles. These files were converted to raster by using the feature to raster toolbox. A problem with the data was that some of the points and lines did not have elevation in the attribute table for example the architectural monuments. When these points and lines were converted to raster, the resulting file contained some cells with 0 values which were unrealistic. Then, the resulting files were combined into new raster layer by using the toolbox Mosaic to New Raster.

The default cell size of 4.63885 m was used. If a smaller cell size is chosen, the resulting raster layer contains more cells with unknown or 0 values. Another reason for selecting the default cell size is that this size provides enough resolution to represent the basic features of the topography.

The resulting raster layer is shown in Figure 6.

Figure 6 Raster Layer of the area in ArcGIS 10

The raster file was converted to ASCII text file using the toolbox Raster to ASCII. In the text file all no value cells represented by -9999 were changed to 0. The reason was that most of these cells were located in the river or the two canals and for this project there are considered to have 0 elevation.

Land Use Data

By converting the AutoCAD data to raster, a land use map was obtained. The same procedure was followed as for the elevation data. The difference was that when the vector data was converted, instead of elevation the field value for conversion was set to color. The description in the layer field in the attribute table of the vector layers was used to reclassify the resulting raster to land, buildings and parks. The no data values were classified as water.

Rainfall Data

The rainfall data was provided by Claes Hernebring from DHI Sweden. The data contained measurements from the Barlastplatsen weather station in Gothenburg for rain events from 2000 to 2010. The data for the precipitation for 2000 and 2001 could not be used because measurements were taken at every ten minutes and a finer time resolution was needed. Three rainfall events were selected in 2002, 2003 and 2010. The rainfall event in 2002 has higher intensity than most of the other rainfall, the precipitation in 2003 is average intensity and total volume and the precipitation event in 2010 had long duration and high total rain volume. By using data for the return period of block rain from the report "Rain Intensity in Sweden-Climate Analysis"(Regnintensitet i Sverige – en klimatologisk analys) by Bengt Dahlström in 2006, the return period of the events could be estimated. The rain event in 2002 occurred on June 18 and was three hours between 21:00 and 24:00 and had a return period of approximately 2 years. The event in 2003 was on July 17 and was also three hours from 17:00 to 20:00 and had a return period of around 0.5 years and the rain event in 2010 was on August 12 from 21:30 to 6:20 so the return period was around 5 years. The three events which were selected are therefore representative of rainfall that can frequently occur in Gothenburg. The data had fine resolution with measurements every minute.

Setting up the Model

Bathymetry

The bathymetry file was created in MIKE21 using the Mike Zero toolbox. The tool Grd2MIKE was used to convert the raster in ASCII file format to dfs2 file which can be used with MIKE21. The values at the end rows and columns are assumed to be the boundaries for the model and were changed to 1000m (Figure7).

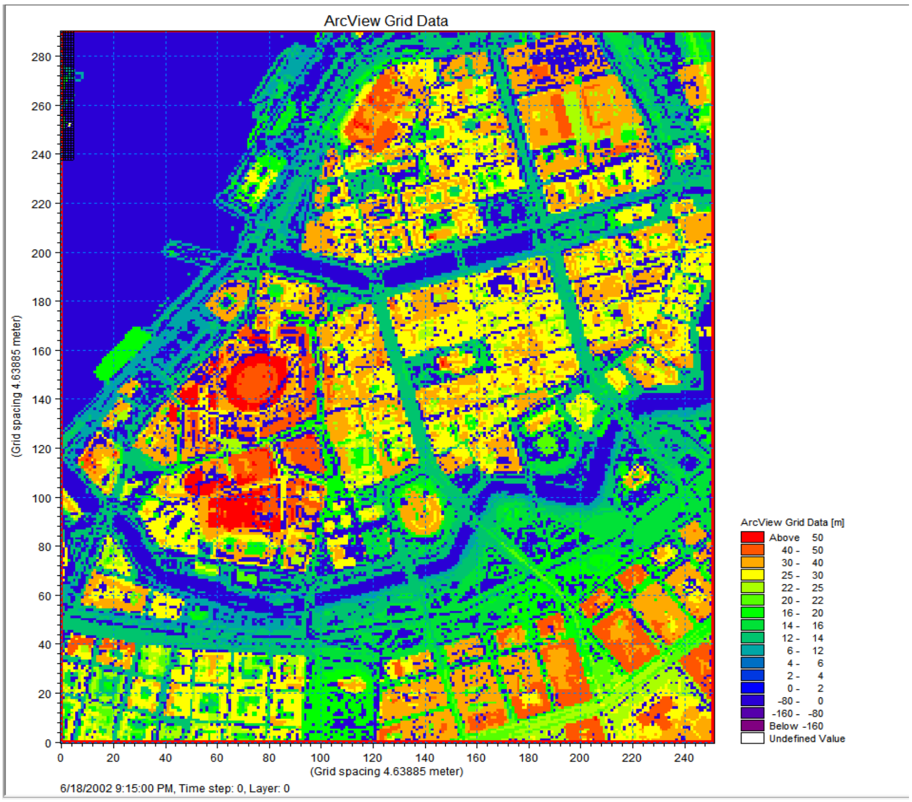

Figure 7 Imported Bathymetry Raster in MIKE 21

The resulting dfs2 file contained areas that had unrealistic elevation of 0m located mostly in the harbor or around the streets and in the parks. They resulted in a number of sinks (depressions) and, because they were surrounded by cells with higher elevation and had no outlet after running the model, these cells had very high water level. The depressions in the topography can be classified as real depressions or artifact depressions (Dhun, 2011). The artifact depressions result either from errors in data collection (Aguilar et al., 2005) because the data had low resolution or during the process of data conversion to raster (Aguilar et al., 2005). The sinks need to be removed from the bathymetry because they result in changes to the flow path of the flood water (Thompson et al., 2001).

The area was compared with Google Earth so that only the natural depressions are kept (Figure 8). Then, all other depressions which had a value of 0m were deleted (Figure 9). The interpolation tool in MIKE21 was used to assign values to the areas with no data (Figure 10). For some values that were closed to the canals or the river, the interpolation tool could not be used because, due to the proximity of many 0m values, the interpolated values were very low.

Figure 8 Overlay on Google Map

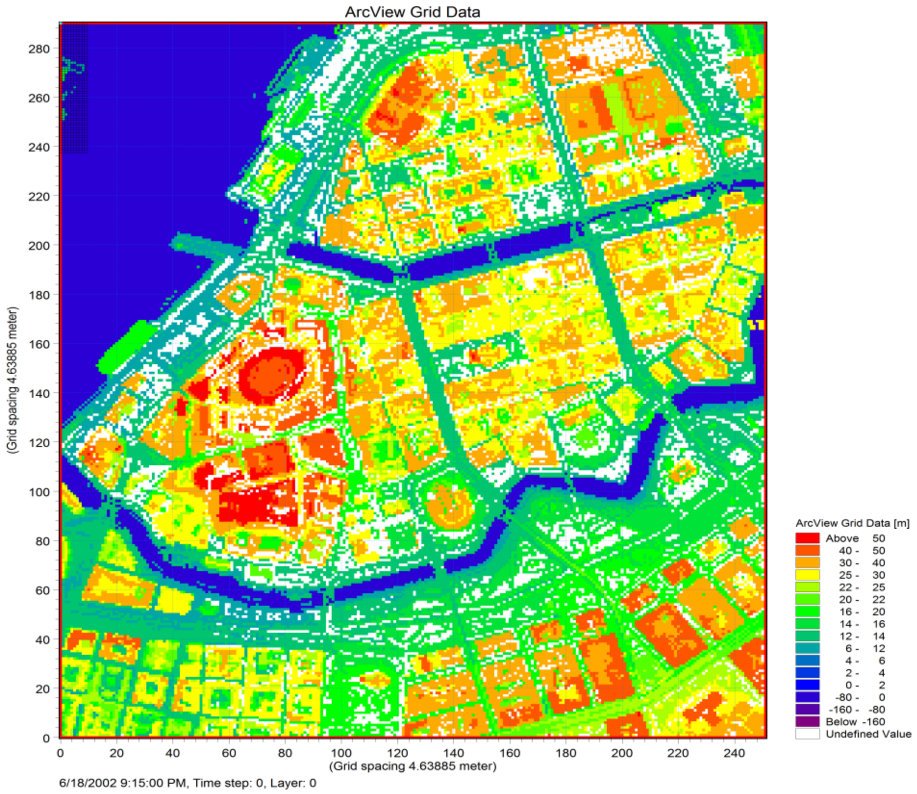

Figure 9 Deleted Values in the grid represented by white

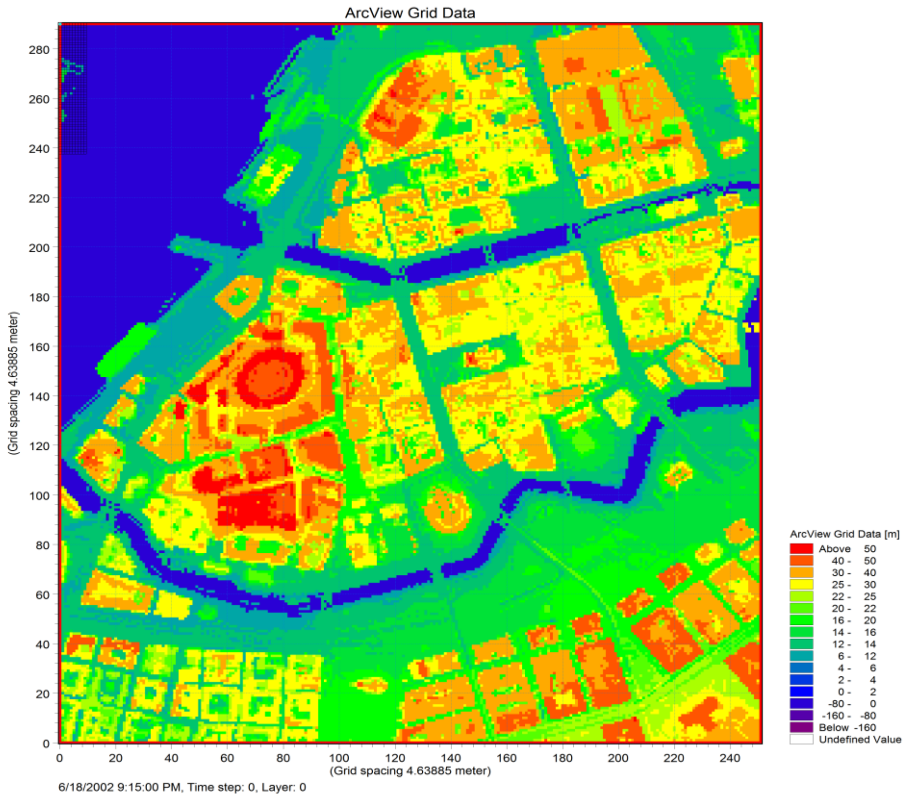

Figure 10 Interpolated elevation values

The bridges in the canals were removed from the bathymetry because they cannot be modeled in MIKE 21 and block the water flow (Figure 11).

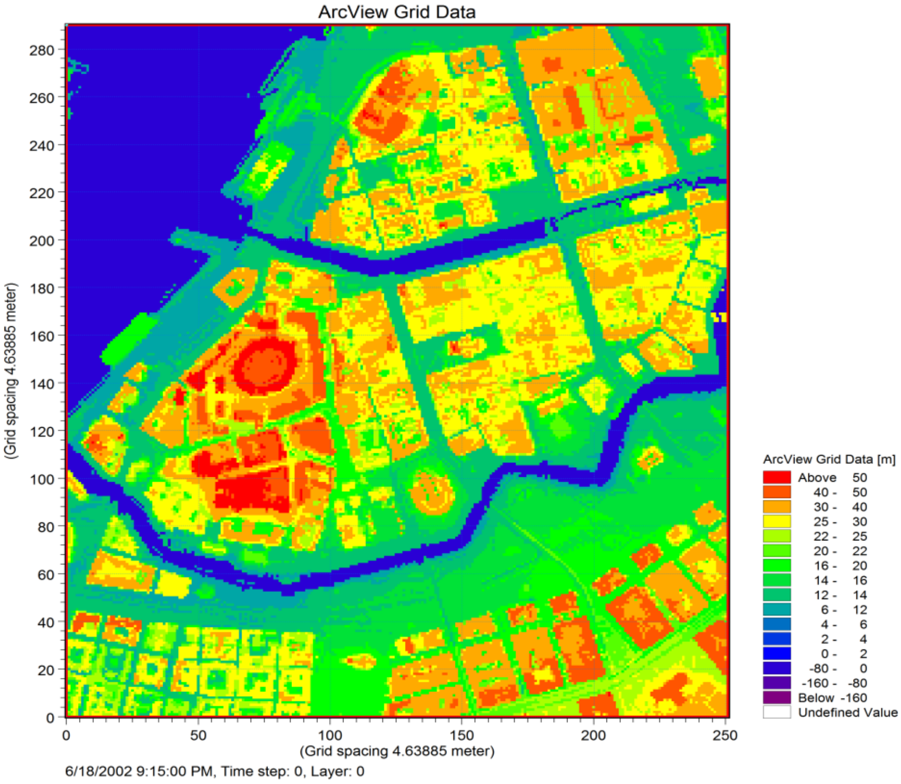

Figure 11 Deleted Bridges in the grid

Time Step

Choosing smaller time step results in higher stability of the model (DHI , n.d.). The Courant number has to be less than 1 (DHI , n.d.). The Courant number is the number of grid points which are part of the calculation for a time step.

$$c_r = c\frac{\Delta t}{\Delta x}$$

Where:

c- wave celerity or U max
t- time step
x- grid spacing
The number of time steps affects the CPU time. In the model a time step of 0.1s was chosen. The time step increased the processor time but because the area was relatively small, the CPU time was not a consideration.

Flooding and Drying

The recommended range for flooding depth by MIKE21 is 0.001 to 0.02 and for drying depth is 0.002 to 0.04 (DHI, 2011). Several simulations were done in order to determine the optimal values within this range. The value of 0.001m was used for flooding depth. Different values were used for the drying depth for the three rainfall events to obtain more realistic water depths. For the rain events in 2002 and 2010, the value of 0.017 was used and for the rain event in 2003, 0.014 was used. The drying depth is the minimum value at which the cell is taken out of the calculations. To make the flood and dry algorithm more efficient, this occurs when the cell is surrounded by other cells that are dry. If the water level in the cell is between the drying and flooding depth or borders wet cells, the grid cell is partially dry and only the mass balance equation is solved (DHI, 2011). The point reenters the computational grid when it is at the flooding depth. If drying occurs immediately after flooding, this can result in instability of the model (DHI , n.d.). The difference between the flooding and drying depth was chosen to be larger as recommended by MIKE 21.

Eddy Viscosity

The eddy viscosity is defined as:

$$\tau_0 = \eta \frac{\partial \bar{u}}{\partial z}$$

Where:

τ_0 - wall shear stress

η- eddy viscosity

$\frac{\partial \bar{u}}{\partial z}$ - change of the mean horizontal velocity along depth

The eddy viscosity would affect the model if there is a change in the velocity. The change would be around the buildings and near the harbor and when the flow path changes. In MIKE21, the eddy viscosity can be as constant value or expressed by the Smagorinsky formula. If the eddy viscosity is set to 0, then oscillatory eddies can form and if the value is high than there would be no effect on the flow (Syme, 2008). A study, Flooding in Urban Areas - 2D Modelling Approaches for Buildings and Fences, recommended the value for the eddy viscosity to be a maximum of 0.5 in urban areas so, in the model, the value of 0.5 was used (Syme, 2008). The recommendation by MIKE21 for using constant and flux based value was also followed (DHI , n.d.).

Manning Number

The Manning number affects mostly the flow path and the peak time and almost does not have effect on the flood area and depth (Wang & Hartnack, 2006). A DHI study in Germany showed that most appropriate values for the Manning number are 15 to 25 in urban areas (Wang & Hartnack, 2006). The model is in urban area with some parks around the canals. Two simulations for each rainfall event were done: first, a constant Manning number of 14 was used for the entire area because of the high number of buildings and the second time, a land use map with different values was used. The land use map classified the area into buildings, roads, parks and water. The buildings which have a value of M=3 are represented by their real elevation and obstruct the flow so the flow depth in these areas would not make so much difference. Using a land use map gives better approximation of the friction which would affect especially the areas in the canal because water was set to M= 76, the parks which have values of M=20 and the roads of M= 71 (Table 2).

Table 2 Manning Numbers, values from Sanders, n.d. and Syme, 2008

Land Use	Manning's n	Manning Number
Buildings	0.33	3
Parks	0.05	20
Canals and River	0.0133	76
Roads	0.014	71

The approximation of the values for the Manning number was based on referring to values used in other studies (Baldwin Hills Dam-Break Flood). Often, the values for the Manning number are obtained during calibration. However, for the chosen flood events there was no available data for calibration. Figure 12 shows the Manning number used in the simulation.

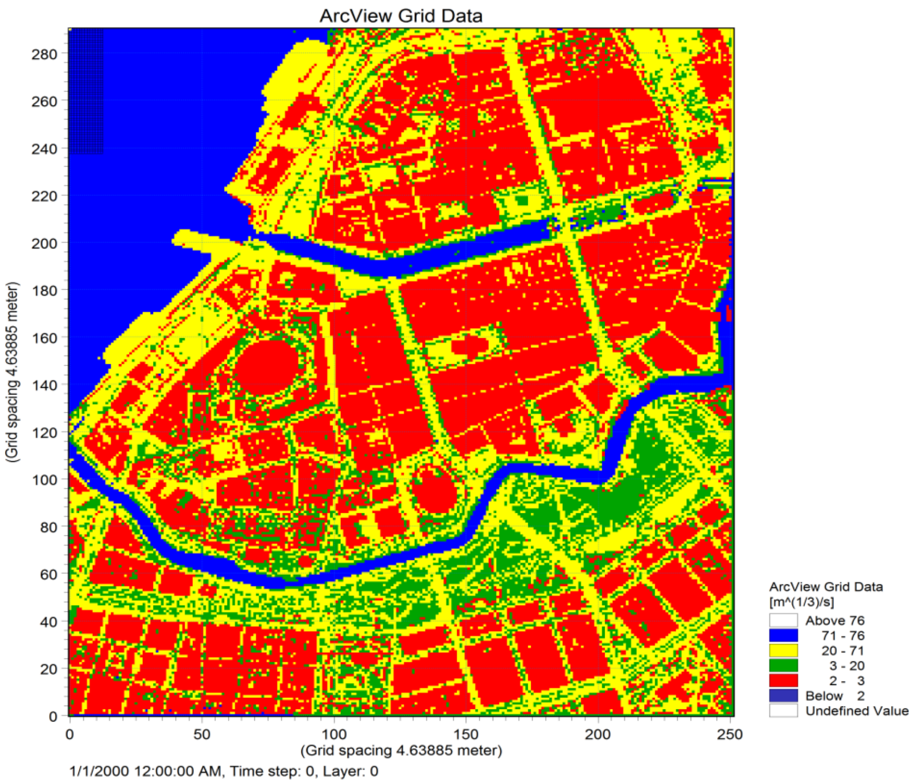

Figure 12 Grid file for Manning Numbers

Rainfall

The rainfall data was converted from mm/min to mm/day. The values were imported to MIKE21 using new time series file in dfs0 format. Three rainfall events were simulated. The precipitation event in June 18, 2002 between 21:00 and 24:00 had the highest maximum value from the three events of 1.87 mm/min and the total rainfall is 18.2 mm (Figure 13).

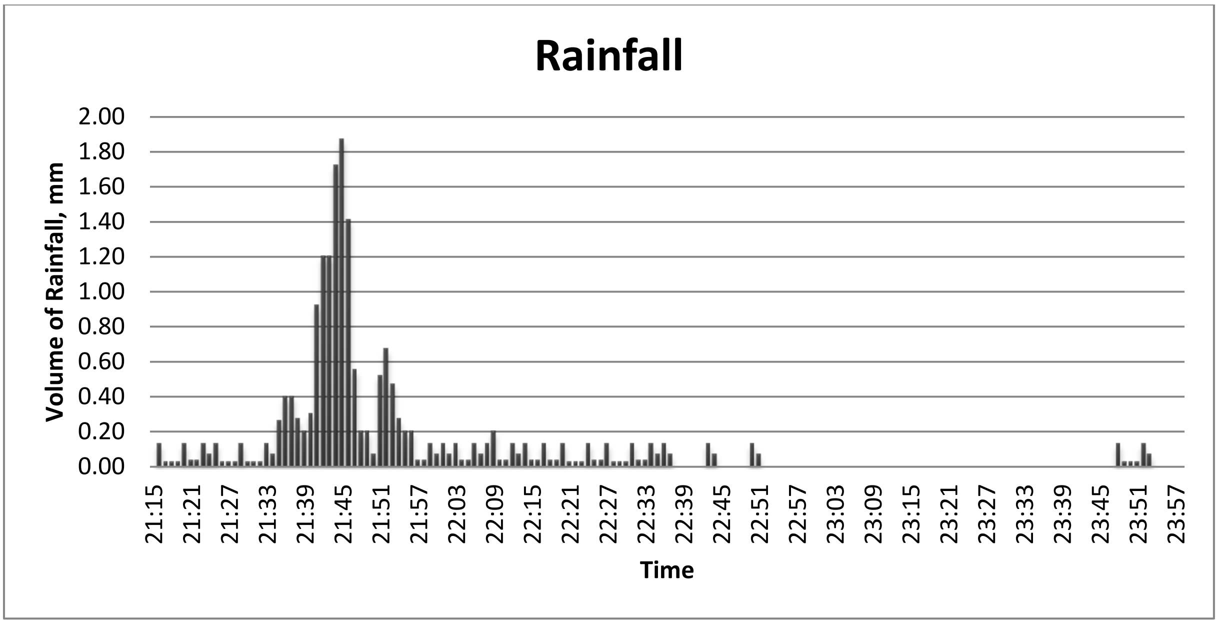

Figure 13 Precipitation on 18-06-2002

The event in July 17, 2003 had lower maximum value 1.11 mm/min and the total amount of rainfall was lower 14.7 mm (Figure 14).

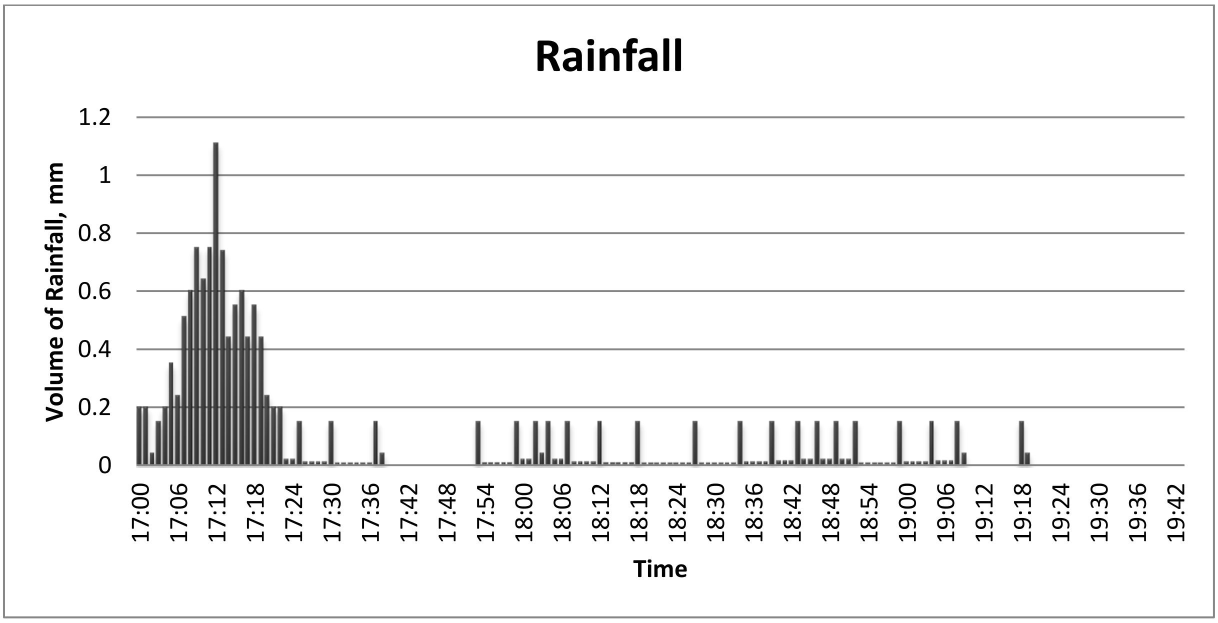

Figure 14 Precipitation on 17-07 -2003

The rainfall in 2010, on August 12, has the lowest maximum value of 0.93 mm/ min but the highest total volume of 37.6 mm (Figure 15).

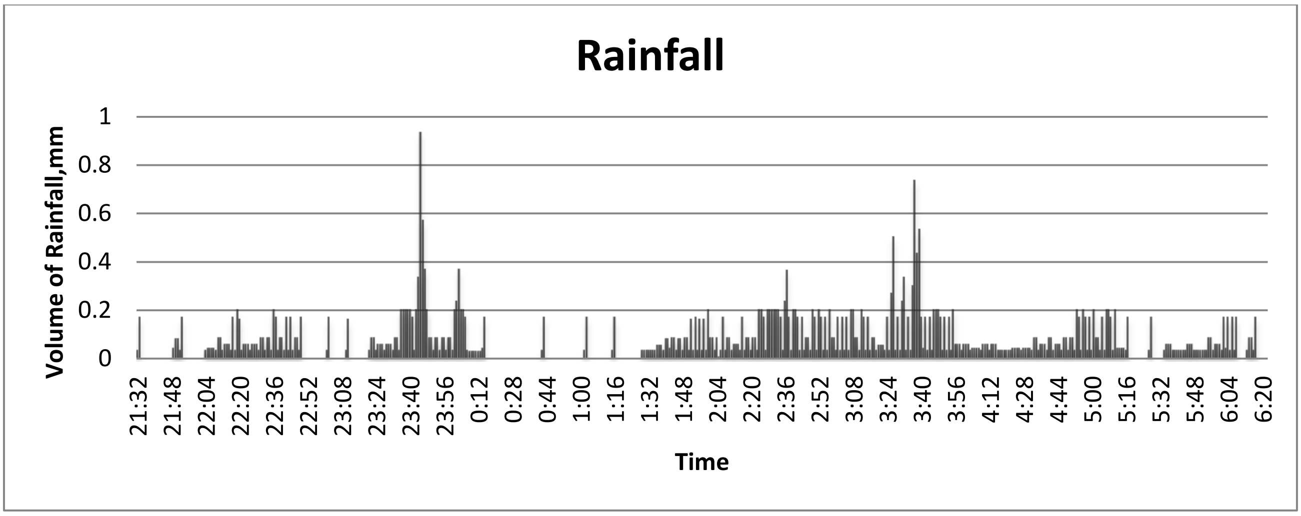

Figure 15 Precipitation on 08-12-2010

Results

Rainfall Event in 2002

The results show that the lower lying areas would be flooded and especially the streets between the buildings, some major roads like Östra Hamngatan and Magasingatan and some areas in the harbor (Figure 16). The mean sea level is 9.96m so the areas that are lower than this level are more likely to be flooded. The water level on Östra Hamngatan and Magasingatan is over 0.5 m and at 0.5 m cars and vans become unstable (Defra / Environment Agency, 2006). In some places, the space between the buildings would be flooded because there is no route for the water to exit. If a drainage system with appropriate capacity was considered, then the water depth would have been less. The water level in the Stora Hamn canal is around 0.44m and in Rosenlund canal, the flood depth reaches up to a meter.

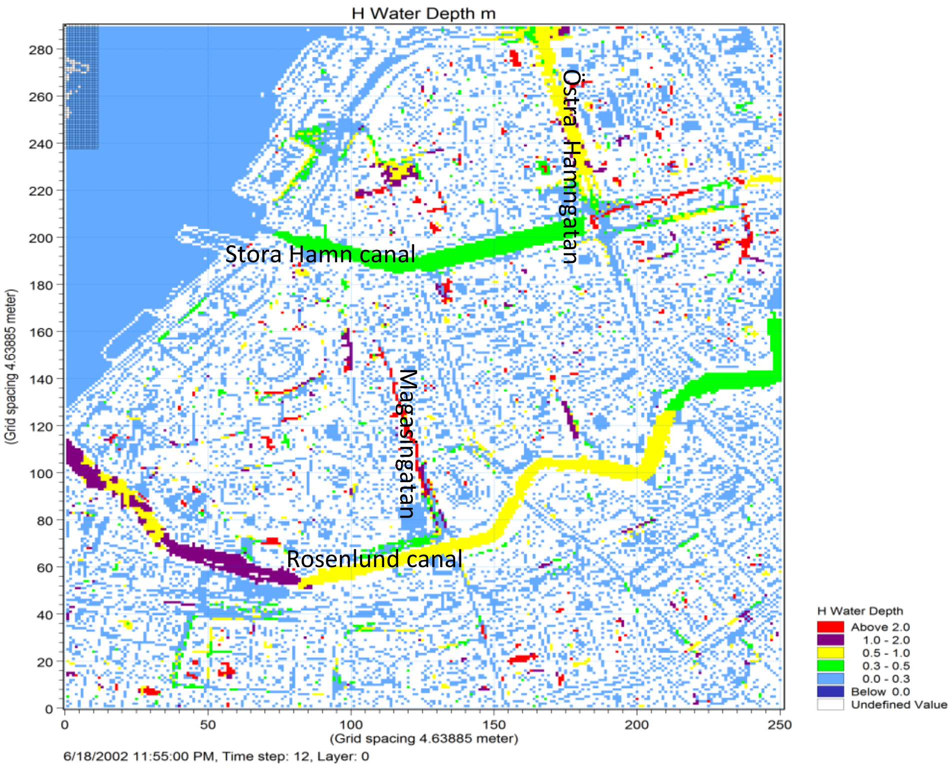

Figure 16 Water Depth Resulting from constant Manning Number

The percent inundated area does not take into account the buildings which are 41.4 % of the area. From the majority of the remaining area, which is 58.6 %, around 50% had water level below 0.3 m. Most areas that were flooded between 0.3 m and 1 m were located in the canals and major roads and the harbor. The water levels above 1m, which is 2.3%, occurred mostly in the streets and in the spaces between the buildings. Figure 17 shows a chart with the values.

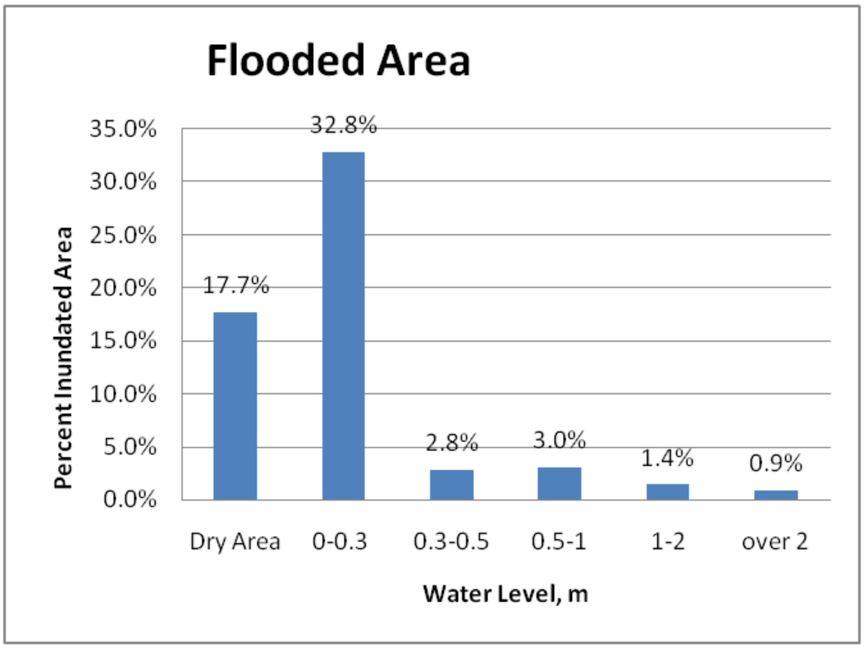

Figure 17 Percent of Flooded Area on 18-06-2002

The results for the water depth show that the difference in Manning number mostly affects the water depth in the canals (Figure 18). Because a much higher Manning number was used in the parks – 20 (n=0.05) compared to the constant number of 14 – the water level in the canals increases. The same way, the water level in the harbor is higher because roads or asphalt surfaces were assigned a Manning number of 71. The water level in the parks also increased because of the lower resistance to the flow.

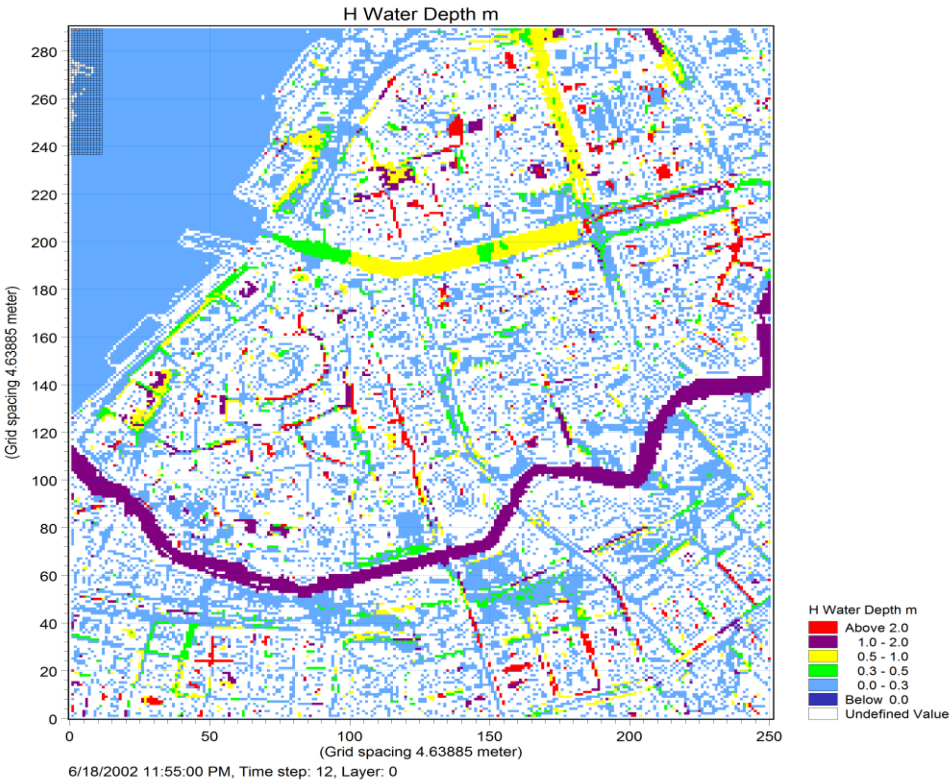

Figure 18 Water Depth with Manning numbers from Land use Map

The water level in the Rosenlund canal is over 1m and in the Stora Hamn canal is over 0.5m so the number of areas with greater depth than 0.5 m is much higher; over 11% of the area (fig. 19). The area with flood depth of over 2 m which is mostly around the buildings increased from 0.9% to 2.5% .The percent of area which has a water depth between 0 and 0.3 is higher too around 34 % because the park is also flooded more.

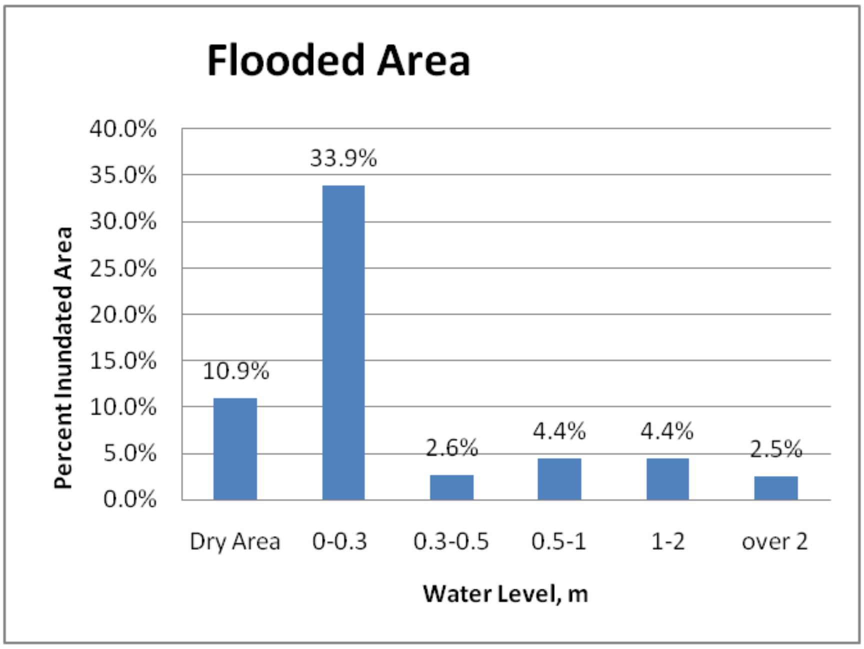

Figure 19 Water Depth chart

The flood velocity is an important parameter because higher velocity increases the damage to buildings and roads and limits the time for evacuation and flood protection measures. The combination of flood depth and flow velocity also needs to be evaluated. A single story building would be damaged by 0.5 m flood with velocity of 4 m/s while if the flood velocity is 0 m/s the building would be damaged if the water level is above 3 m (Kreibich & Piroth, 2009). A study, "Is flow velocity a significant parameter in flood damage modelling?," by Kreibich, H et al. published in 2009 finds that only a combination of high flood depth and flood velocity would lead to major damage of residential buildings and that there is no clear relation between just the flood velocity and damage to the buildings. However, flood velocity is important if damage to the roads is considered. The flood velocity has more impact on road damage than the flood depth while the opposite is true for buildings.

The average velocity in the model is very low, around 0.013m/s at the last time step. The highest average velocity occurs at the moments of maximum inundation because most points are partially wet or wet; 66000 out of 73310. The velocities at the last time step are presented in the results because they can clearly show the difference between using constant and distributed Manning number. In addition, excluding the steps where most of the area is inundated, the average velocities are higher at the last step because the accumulated water volume is higher. The time steps when most of the model is inundated can be excluded also because the water level and flood velocities are relatively small compared to other time steps. Another limitation of the model is that there is no boundary hydrograph for the river and the land boundaries limit the flow of the river so that the water level and the velocities in the river are inaccurate. In the end of the rainfall, the velocity is highest on the street Magasingatan (fig 20) .

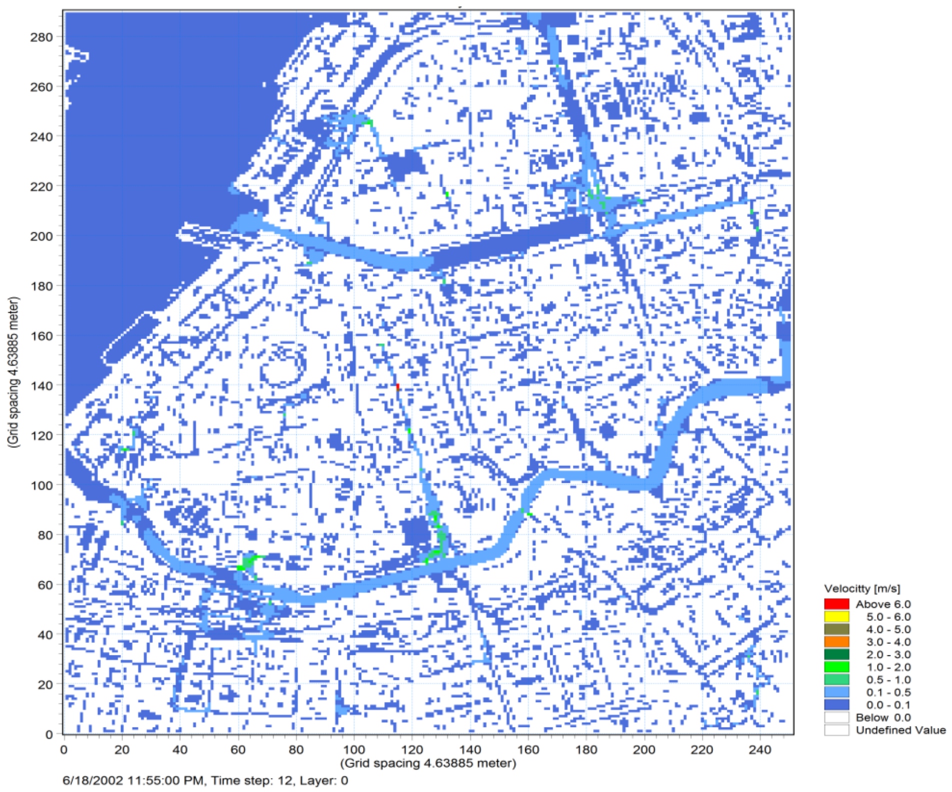

Figure 20 Velocity in the last time step with constant Manning Number

The velocity is highest, around 10 m/s, at 23:00 at the intersection of Kungsgatan and Magasingatan (fig 21). Most water flows to the two canals or the river.

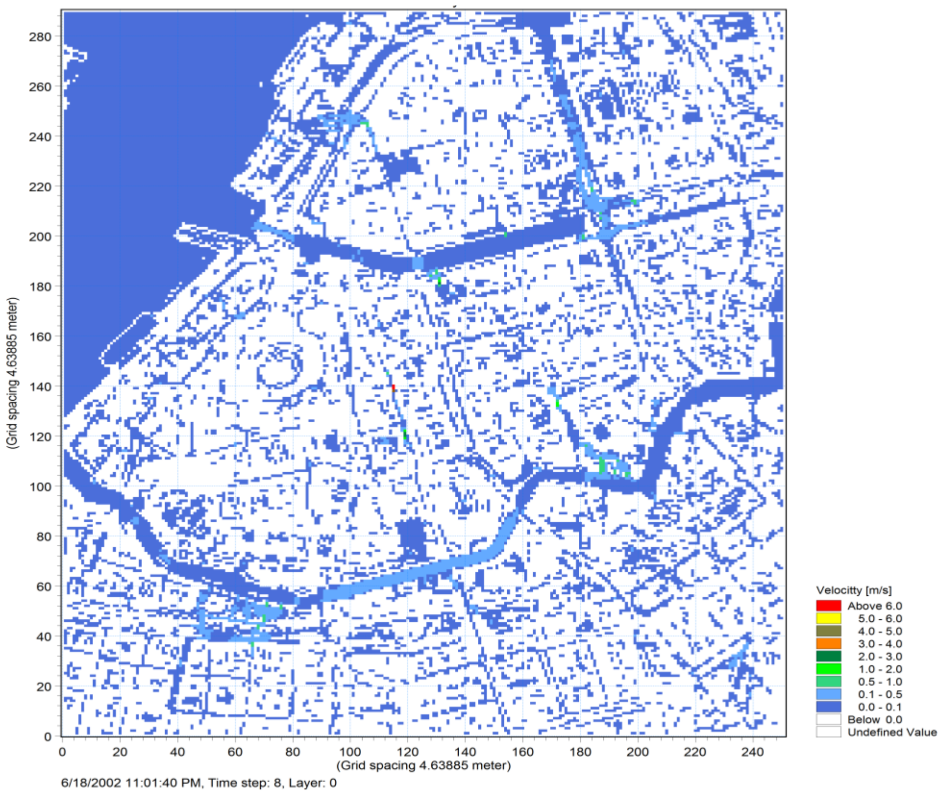

Figure 21 Highest Flow Velocity

The velocities in the canals, the parks and the river increase if values for the Manning numbers were used based on the land use map. Figure 22 shows the velocity at the last time step. The increase in Manning number (M=1/n) represents the lower resistance of the flow (lower n) and the velocity would increase in this area. The average velocity increases to 0.035 m/s.

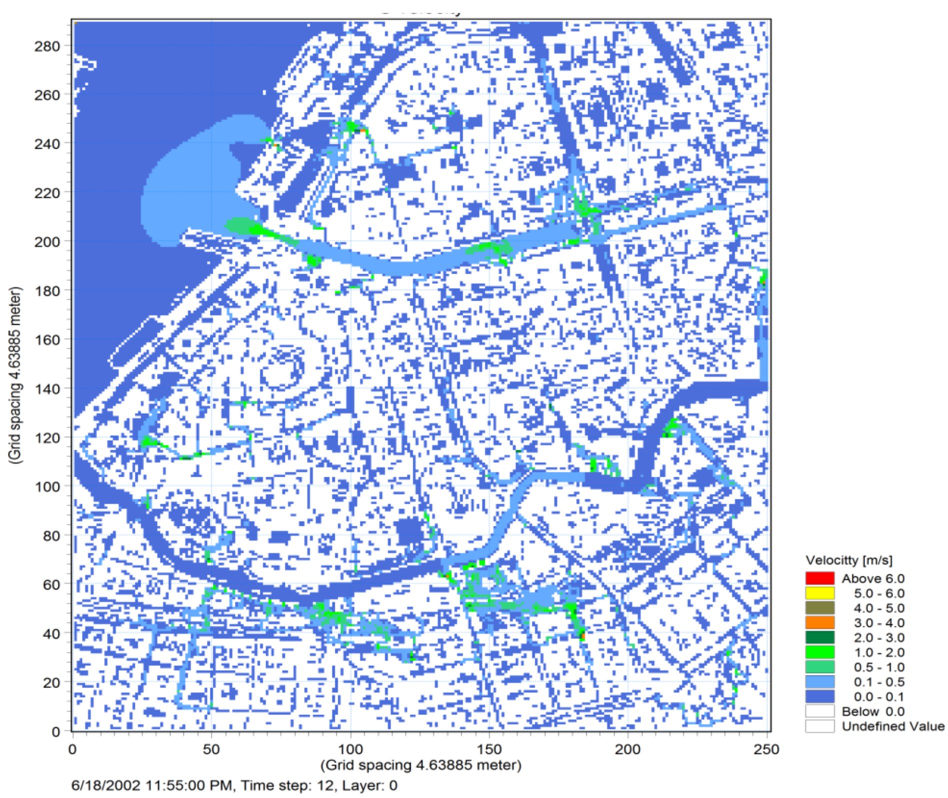

Figure 22 Flow Velocity with distributed Manning numbers

If distributed Manning numbers are used, the velocity would be maximum at 22:35, around 10 m/s, at the intersection of Kungsgatan and Magasingaran (fig 23). A possible reason is that the slope near this point is very steep.

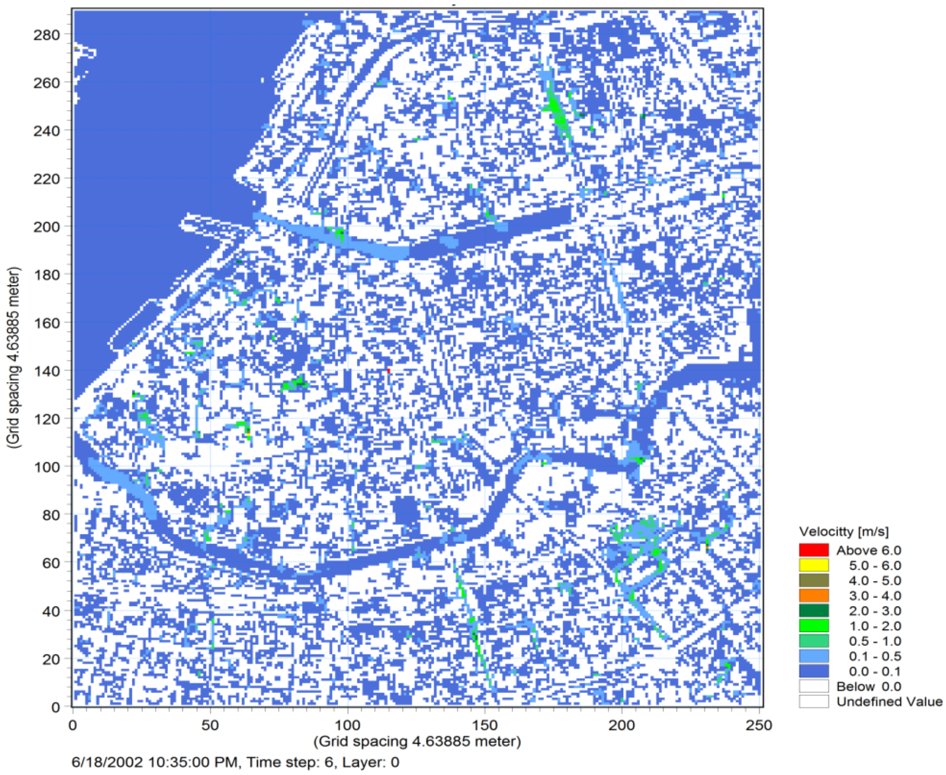

Figure 23 Highest Flow velocity

Rainfall Event in 2003

The results are similar to the rainfall event in 2002 and they show that there is a minimal increase in the depth of the canals and flooding in the space between the buildings and some streets like Magasingatan (Figure 24).

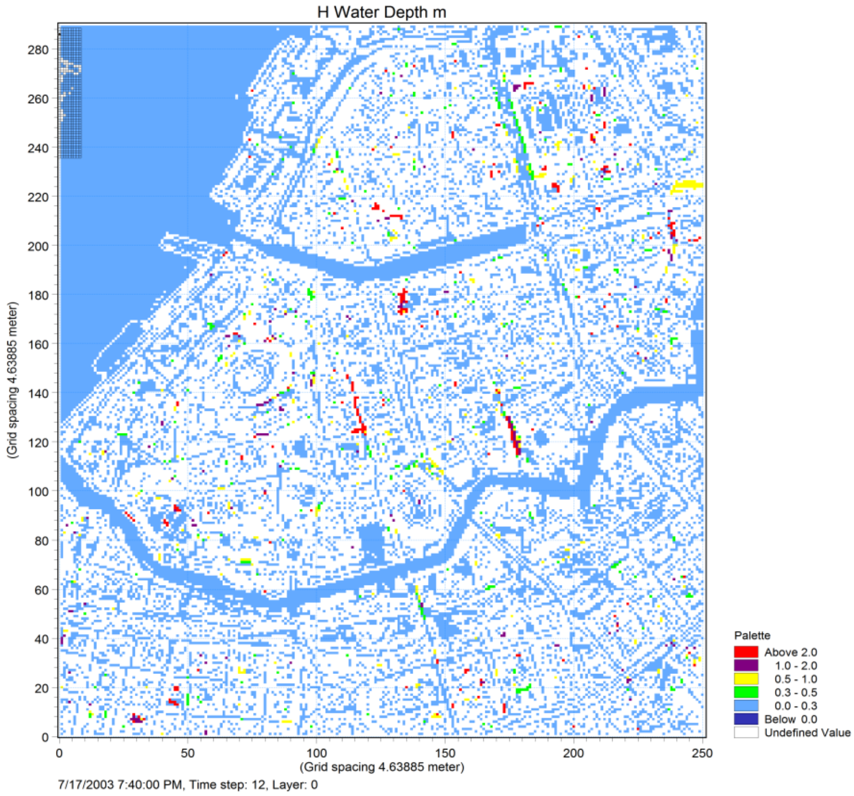

Figure 24 Water Depth if constant Manning number is used

The flood depth is less than the event in 2002 which can be expected because the maximum value and total amount of rainfall is less. Almost all area is not flooded or has less than 0.3 m water depth. Only 1.5 % of the area is flooded above 0.3 m. The water depth around the buildings and some small streets is above 2m which is 0.35% of the study area (Figure 25).

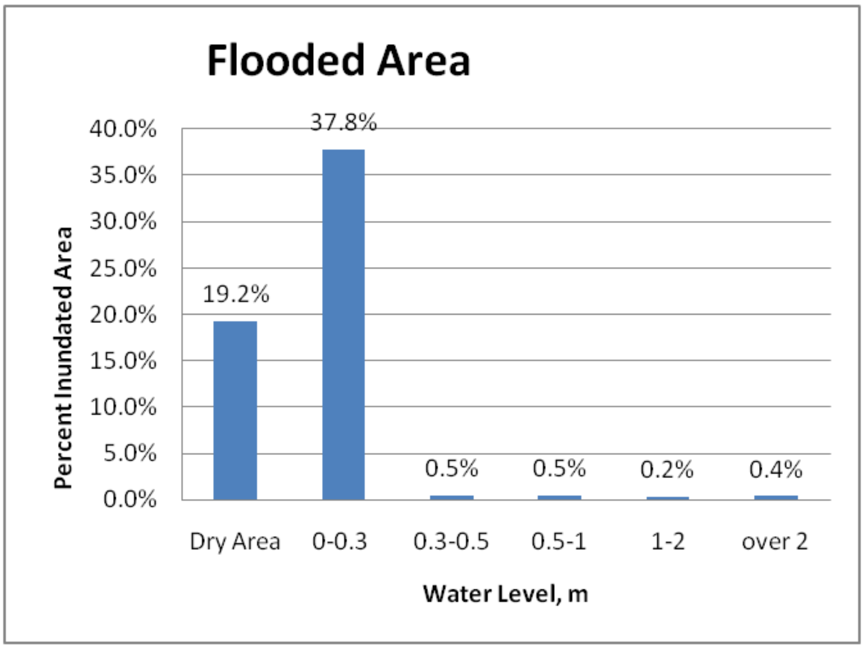

Figure 25 Percent Flooded Area

The water depth increased in some streets like Östra Hamngatan, in the parks and the Rosenlund canal if the Manning number that is from the land use map is used (Figure 26).

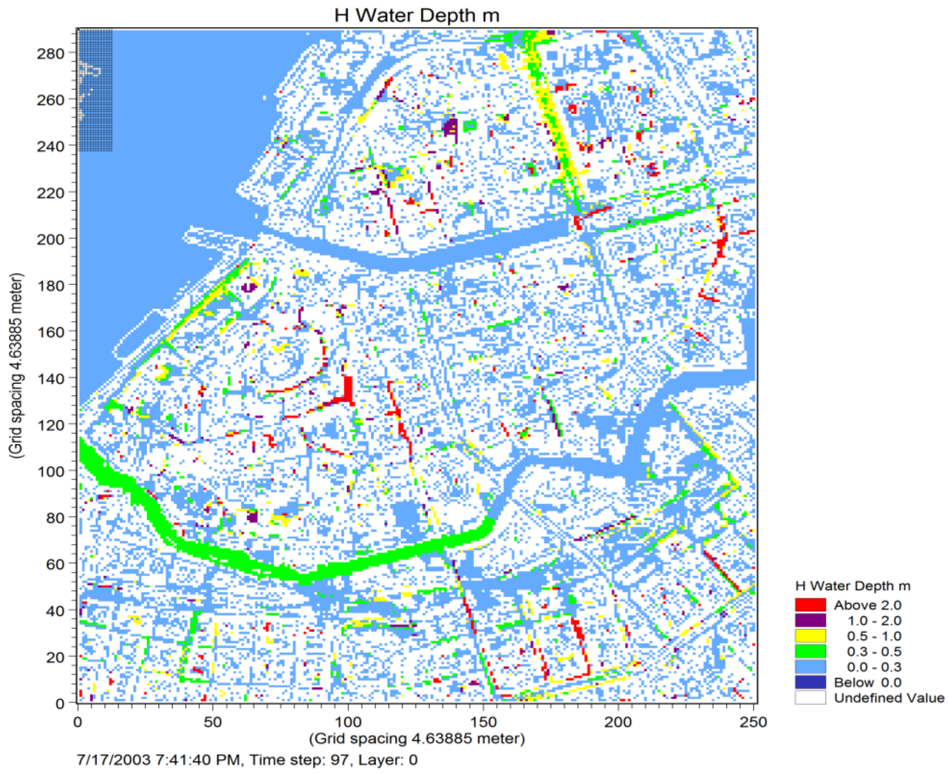

Figure 26 Water Depth with distributed Manning Numbers

Most of the area, around 88.3%, has water depth less than 0.3 m which is much less than if constant Manning number is used. There is an increase to around 4.45% of the areas which are flooded between 0.3 m and 0.5 m and between 0.5 m and 1 m (Figure 27). This increase can be explained because the water level in the Rosenlund canal and Östra Hamn street has significantly increased.

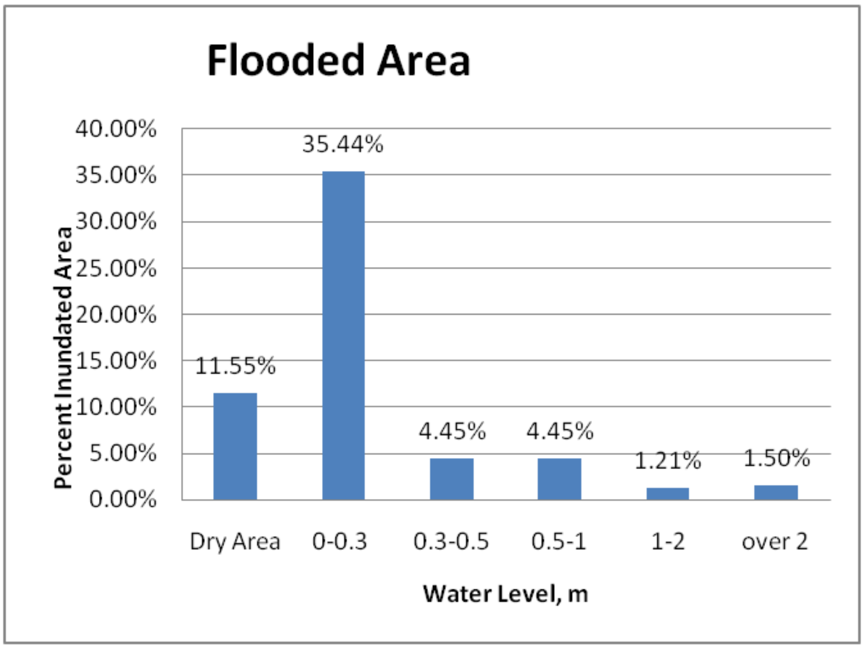

Figure 27 Percent Flooded Area

The highest velocity and the velocities in the last time step for each method are shown in appendix I and appendix II.

Rain Event in 2010

The total amount of rain is much higher compared to the events in 2002 and 2003 and the results show that the area is flooded more. The water level in the two canals is very high. In Rosenlund canal the water level is around 8.7 m and in Stora Hamn canal , the water level is around 2.5 m. The water level in the Göta River is also 2.3m. In the same way as for the event in 2002, the streets Östra Hamngatan and Magasingatan are flooded (Figure 28). The space between the buildings is still significantly flooded with water depth reaching above 14m in Otterhällen. The park around Rosenlund canal is also flooded. An option that MIKE 21 provides is to overlay the flood depths on an aerial image. The overlay is shown in Appendix IV.

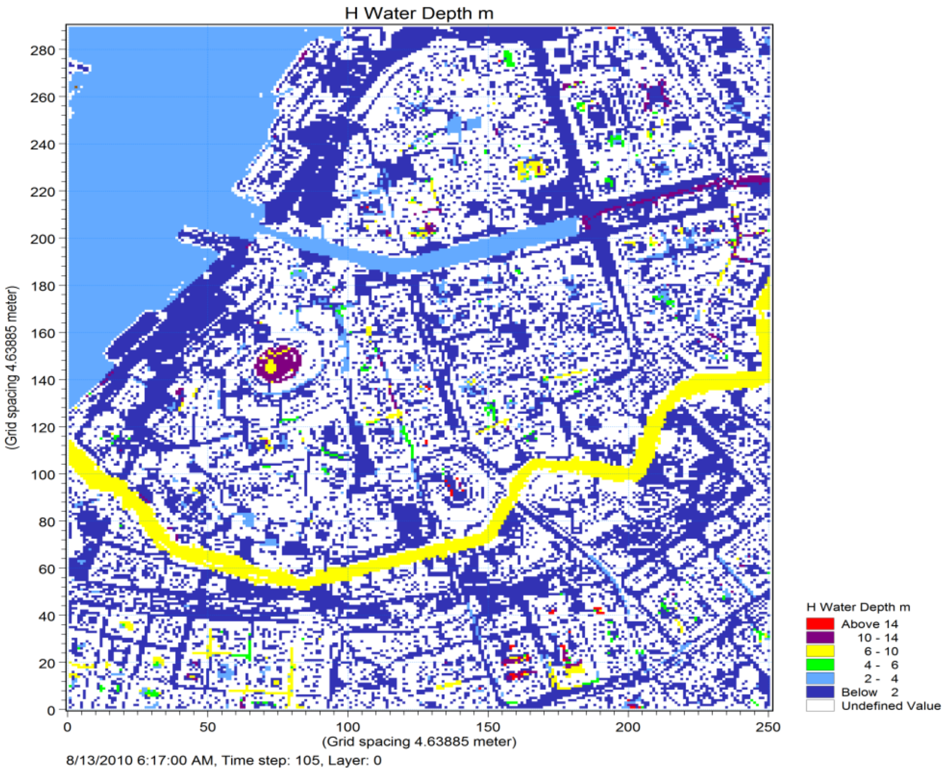

Figure 28 Water depth with constant Manning numbers

The areas which are not flooded, excluding the buildings, are around 7% and they represent the places with higher elevation. The water level in the harbor, the park along the Rosenlund canal and the major roads are flooded with less than 2m which is around 33.2% of the area. The areas flooded with water depth between 2m and 4m are the Göta river and the Stora Hamn canal . The areas flooded between 6m to 10m are 3.4% and this represents the canal. Figure 29 shows a chart of the values.

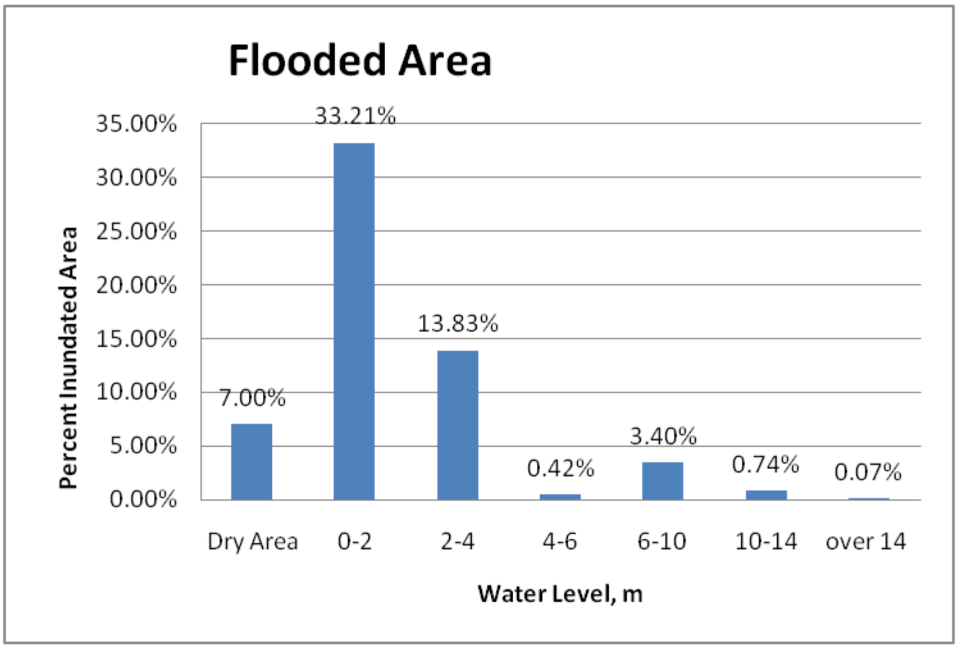

Figure 29 Percent Flooded Area

The results from simulating the rain event with Manning numbers from the land use map (Figure 30) show that the flood depth is increased in the canals, the river and also in the harbor. The park space southwest of Rosenlund canal is also flooded more, especially between Norra and Sodra Allegatan.

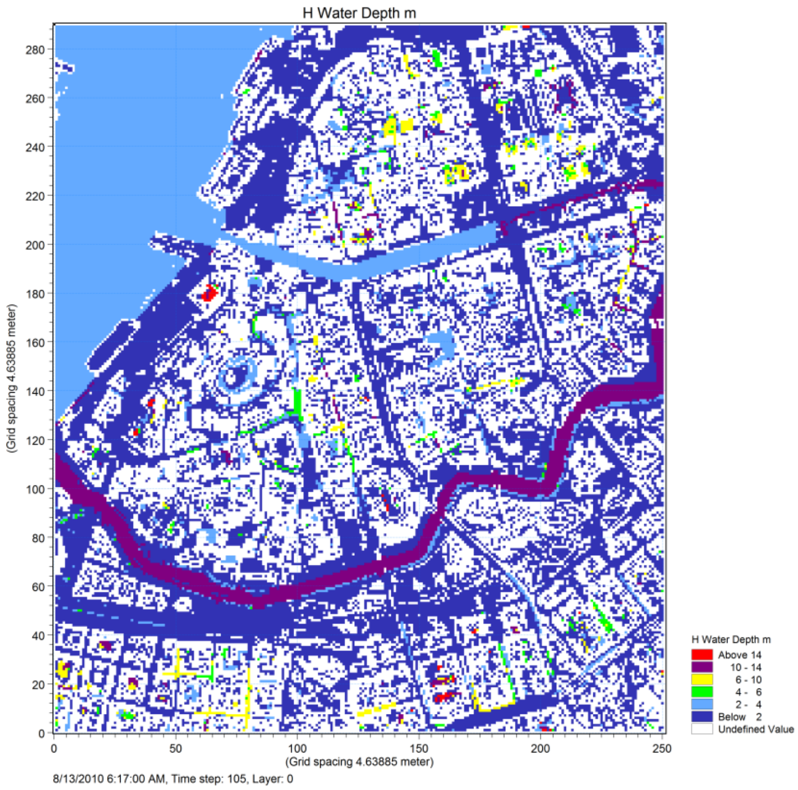

Figure 30 Water Depth from distributed Manning numbers

The percent of areas which are not flooded is lower; 0.3% excluding the buildings. The areas that are flooded with water level below 2m are around 38%, compared to 33.2% with constant Manning numbers. This increase is because more low-lying areas between Norra and Sodra Allegatan are flooded. The percent of areas which are flooded between 10m and 14m is higher - 3.4% - because the water level in Rosenlund canal is higher; around 13m (figure 31).

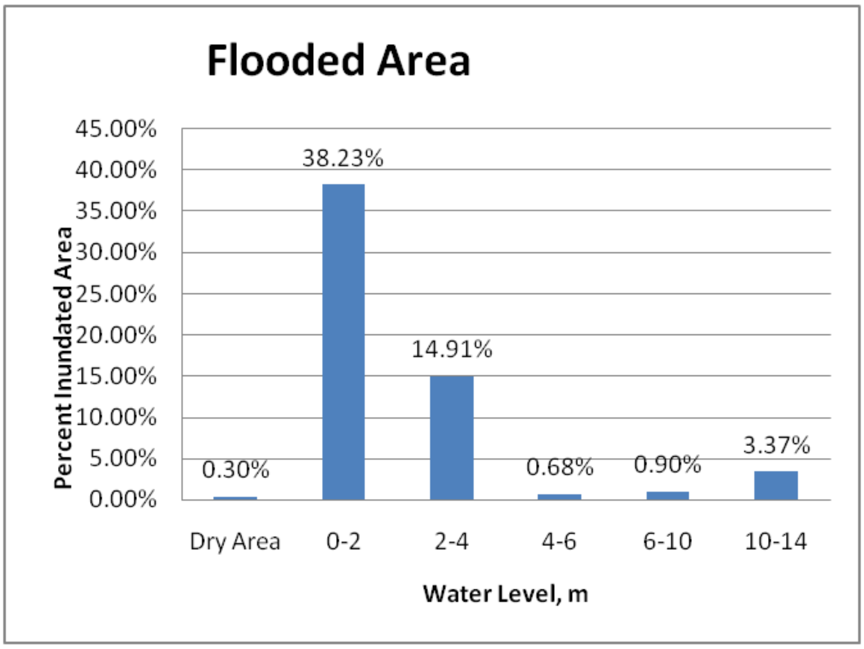

Figure 31 Percent Flooded Area

The maximum velocity and the velocity at the last time step are shown in Appendix I and Appendix II.

Discussion and Further Studies

The results show the areas that can be flooded if the drainage system is overloaded. The model was not calibrated because no accurate historic data was found for the runoff from the three events that were simulated. However, during other flood events, flooding also occurred in the canals and the central part of Gothenburg. In the rainfall event in 2011 on December 10, all the canals within the city were flooded (Sydvik, 2011).

By analyzing the results of the model, the following conclusions can be made:

- A rainfall that has higher total volume and longer duration would cause more flooding in the area than a short rainfall with higher intensity if the drainage system is blocked. Then, if the drainage system is not working, the rain water will accumulate and cause very high water levels. This accumulation of water also causes increase in the flood velocity due to the higher total volume of water compared to a rainfall with higher intensity but shorter duration.
- The highest flood depth is in the small streets or spaces between the buildings. The highest velocities are on Magasingatan and Östra Hamngatan and along Rosenlund canal. Special attention is also needed for the areas in which the flood velocity is very low because if the drainage system is not working, the time of inundation would be very long.
- There is a difference in the water depth and velocity depending upon whether constant or distributed Manning numbers were used. In general, the velocity and water depth increase if the coefficients for the Manning number are based on land use map. The area is very heterogeneous with many buildings which are obstructions to the flow and at the same time roads and parks which have smaller n value. Using distributed Manning numbers would give more realistic results especially when the model cannot be calibrated.
- Alternatives to the combined sewer system or SUDs (Sustainable Urban Drainage Systems) need to be used to supplement the handling of stormwater.

This study identifies the areas for which the city should use further measures to improve the drainage in large stormwater events. Similar conclusions were made by the project, "Plan B – dealing with floods in densely populated cities with extreme rain." In densely populated areas, the areas for infiltration and delay of the stormwater are limited and therefore planning needs to be done in advance. The sewer system in the central part of Gothenburg is combined and, especially if there is an increase in the rainfall, the sewer system would not be able to handle the stormwater. Other alternatives to drainage in the streets and in the space between the buildings have to be in place in case the drainage system is blocked. These alternatives have to also be included in a flood management plan. Methods for local treatment of the stormwater have to also be investigated. The stormwater has to be managed as close to the source as possible. The runoff from impervious surfaces needs to be delayed and treated. The stormwater delay decreases the peak which is especially important to prevent combined sewer overflow. If there are suitable conditions, some or all water has to be infiltrated. However, the groundwater level has to be kept normal so the house foundations and the trees are not damaged. The stormwater is polluted and if discharged directly, there would be need for treatment

(Stadsbyggnadskontoret, 2003). In the planning of new subdivisions, the natural water courses and the low points need to be considered. The use of green roofs and using permeable surfaces is also recommended. The used of open stormwater system sludge has to be maintained by the construction company (Stadsbyggnadskontoret, 2003). Open stormwater systems require more space and this has to be taken into account.

The seminar, Adaptation of Gothenburg to Climate Change, discussed that nowadays, Gothenburg is susceptible to ice storms but otherwise the city is robust to extreme weather. However, because of the climate change, the city is expected in the future to be more vulnerable to extreme weather and some actions are required for protection. To protect the city, it would be necessary to build many customized solutions around Göta River such as: raising the quay, building different types of walls and using provisional protection (Moback, 2011). Also, the sewer system has to be secured so that there is no backflow. An expensive method for flood protection that has been considered, is constructing a barrier on the river delta (Moback, 2011). Another approach is to build basements using materials that can hold against flooding and install pumps to remove the water (Moback, 2011). The water source in Gothenburg also has to be secured. An alternative to Göta River has to be built. The water source was closed for around 100 times per year to ensure safety (Moback, 2011).

Flood risk mapping has been done by using city data and more detailed data from Vattenfall (Moback, 2011). Currently, the city elevation data is being updated to three centimeter accuracy (Moback, 2011). There is also a feasibility study for building a three-dimensional hydromodel which would model risk from the sea, rivers and the sewer system and can be used for flood forecasting and planning (Moback, 2011).

The model would be able to determine the flood risk due to the current conditions and climate change scenarios. The model will include the North Sea, Göta River, Mölndal, Säveån and other smaller streams, flood protection structures, the sewer system and tunnels (Andréasson, 2010). There is currently cooperation between Gothenburg, Mölndal and Härryda in order to prepare a flood forecasting model for the Mölndelsån basin. This model would be used to better regulate the water flow in the rivers in the urban areas and in the lakes upstream. The model can be also used in decision making for choosing better options for preventing floods and efficient usage of the water storage upstream of the lakes (Andréasson, 2010). The municipalities need to coordinate to perform dredging, section increase and strengthening the embankments. By building the Göta tunnel under the central part of Gothenburg, new constructions were made in the seashore region. However, the tunnel has been closed a few times due to flooding (Andréasson, 2010). Landslide archive has also been digitalized (Moback, 2011). The information can be used to evaluate where new buildings can be built and where measures are needed to secure the constructions. There are also new water meters installed and a website would collect and update the data (Moback, 2011).

A pilot study about climate adapted urban structures, part of Mistra Urban Futures, has identified three scenarios for the urban development of the Frihamnsåmrådet in Gothenburg: attack, retreat and defense (Moback, 2011). An attack approach means building structures on pillars or floating devices in the water. Retreat would mean that there would be no construction in the low-lying areas and these areas would be used as parks. Defense would involve continuing to build new embankments and walls, pumping out stormwater and building a spillway. The awareness about the issues was increased after Gudrun and the floods in 2008 and also because of the exposed location of the city (Moback, 2011). One of the thirteen main points in the comprehensive plan for the city is related to planning for extreme weather. There are three strategies: to defend the buildings by building berms, walls and temporary protection and pump out the stormwater, to build in the water by using for example pillars or to retreat and not build in the low-lying areas (Moback, 2011). Another issue discussed is also what the responsibilities would be for the developers, the city and the country (Moback, 2011). The demand to build in the areas near the river is very high and the existing buildings need to be protected. The cost for this protection is 10 billion sek for the central area and 10 billion sek for the surrounding area (Moback, 2011).

In another project, Rivercity Gothenburg, an international workshop of 10 teams of experts was organized to discuss the development of the central part of Gothenburg. A proposal from one of the teams was the increase of porous asphalt, having a network of green spaces and also buildings on floating islands (The RiverCity Gothenburg , 2011). As a structural measure, a wall was proposed around the central part of Gothenburg.Another team proposed new constructions to be built on higher elevations by using fill material and replacing the sewer system with a separate system which can handle the high precipitation and storm surge (The RiverCity Gothenburg , 2011).

The central part of Gothenburg is the area that has the highest risk of floods. However, a flood study is needed for the entire city. The future increase in extreme precipitation, the rise in the sea level and the flooding from the river have to be simulated in a detailed flood study so that the areas with risk of flooding for Gothenburg can be identified. Then, a cost-benefit analysis needs to be done for finding the best set of solutions for flood protection.

Appendix I Velocity for Rain Events in 2003 and 2010

Rainfall Event in 2003 Constant Manning Numbers

The maximum velocity is 2.34 m/s at around 19:30 at the intersection of Korsggatan and Kunggatan (fig 32).

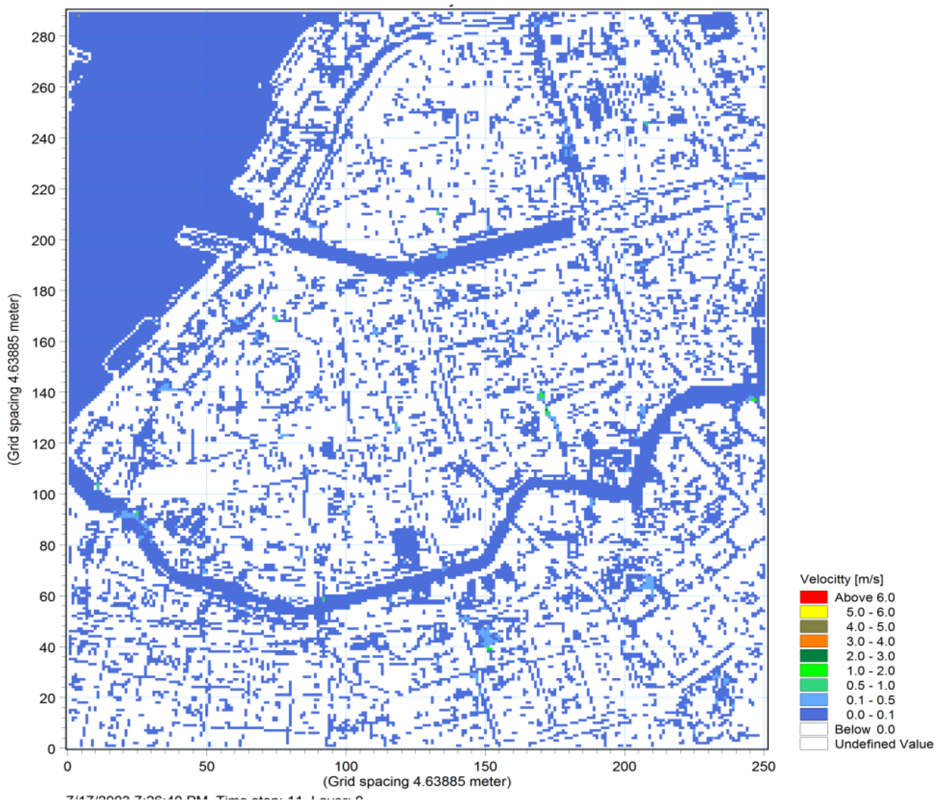

Figure 32 Maximum Velocity with Constant Manning Numbers

Rainfall Event in 2003 Distributed Manning Numbers

The maximum velocity is 14.51 m/s and occurred at 19:11 at the intersection of Kungsgatan and Magasingatan (fig 33).

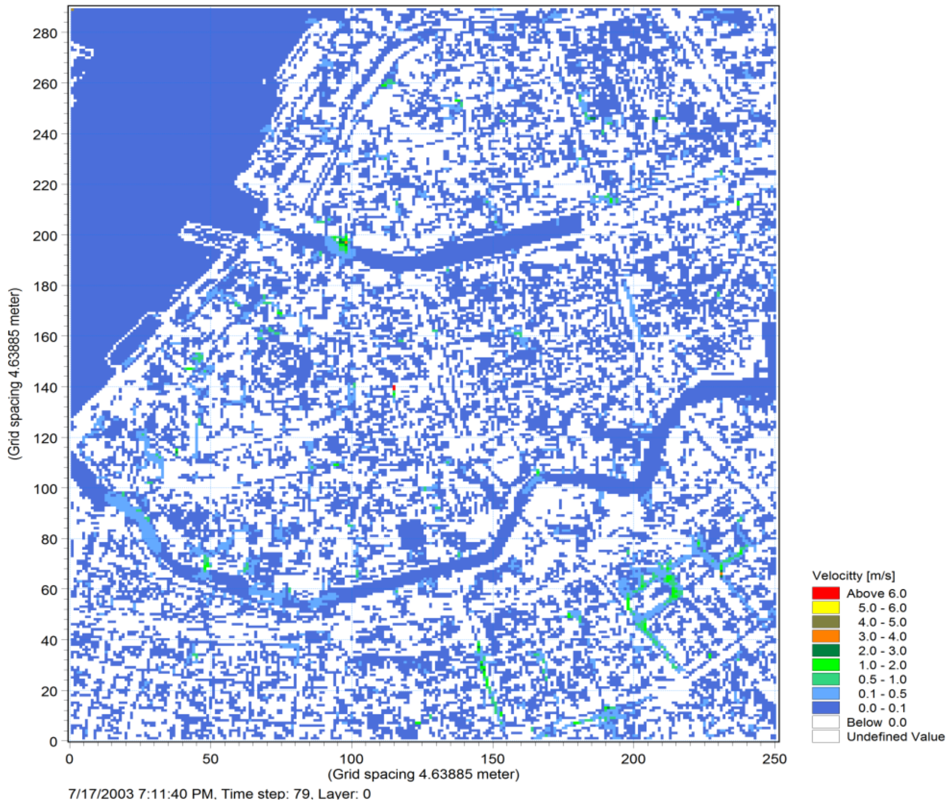

Figure 33 Maximum Velocity in x-direction with Distributed Manning Numbers

Rainfall Event in 2010 Constant Manning Numbers

The maximum velocity is in the Northwest part of Rosenlund canal and is 18.64 m/s. The maximum velocity occurs at 4:32 a.m. (fig 34).

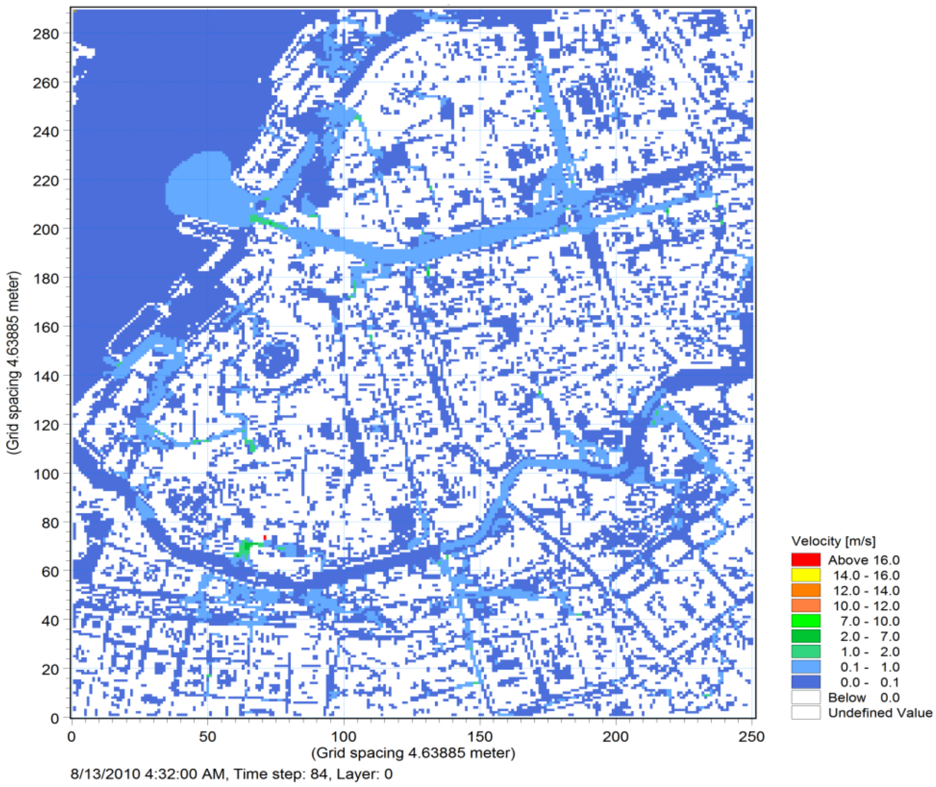

Figure 34 Maximum Velocity with Constant Manning Numbers

Rainfall Event in 2010 Distributed Manning Numbers

The maximum velocity if distributed Manning numbers are used is near Rosenlund canal. The velocity occurs at 4:42a.m. and is around 18.2 m/s (fig 35).

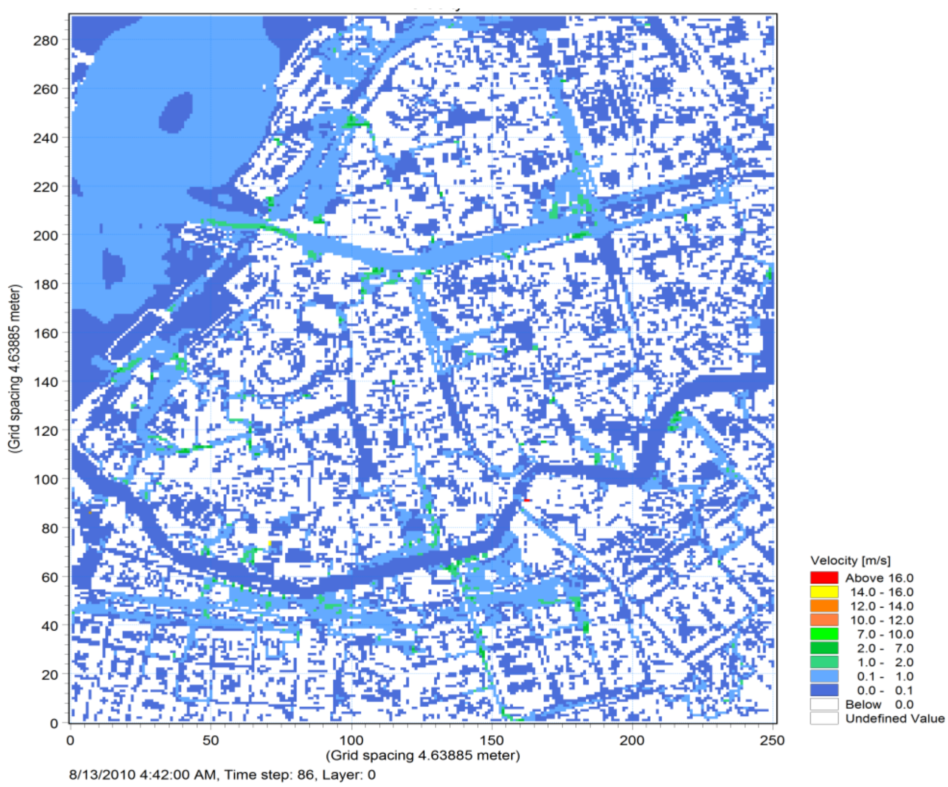

Figure 35 Maximum Velocity in with Distributed Manning Numbers

Appendix II Flow Velocities in the last time step

Flow Velocities for the event in 2003 and 2010 show that if distributed Manning numbers are used, the velocity on the streets and in the canals are higher for the last time step.

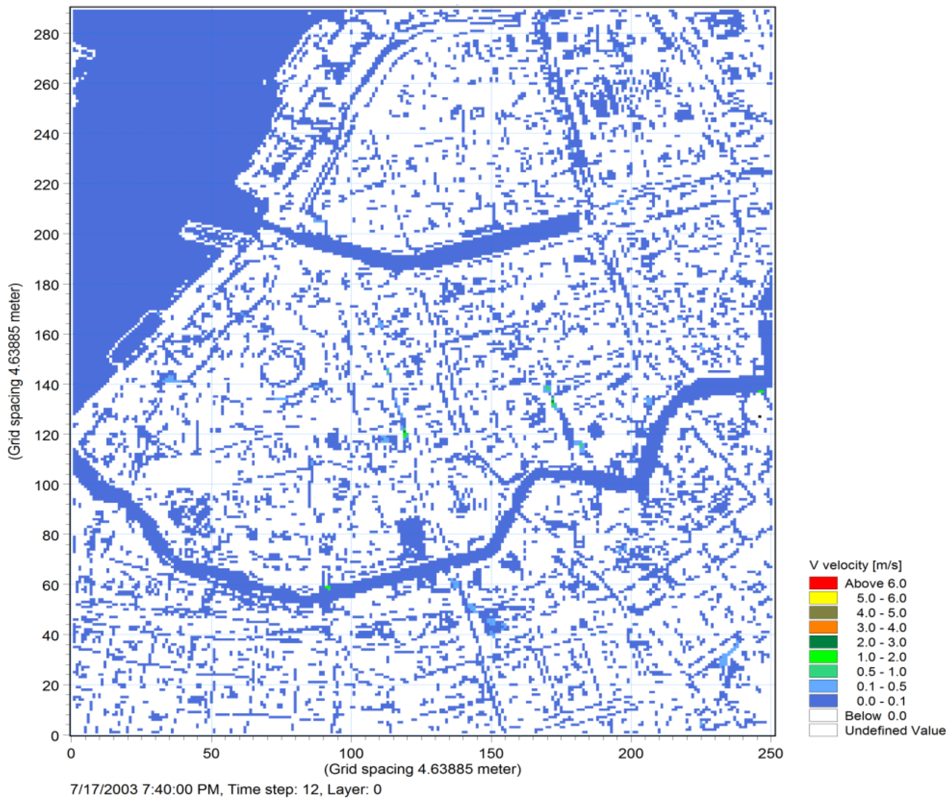

Figure 36 Velocity for flood event in 2003 with constant Manning numbers

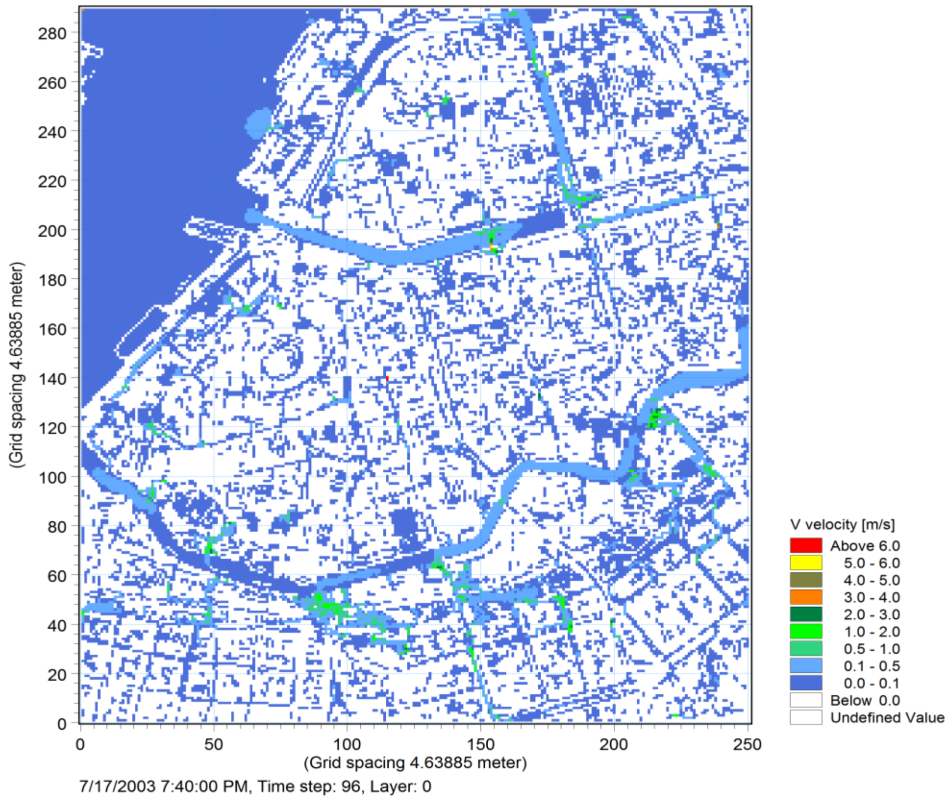

Figure 37 Velocity for flood event in 2003 with distributed Manning numbers

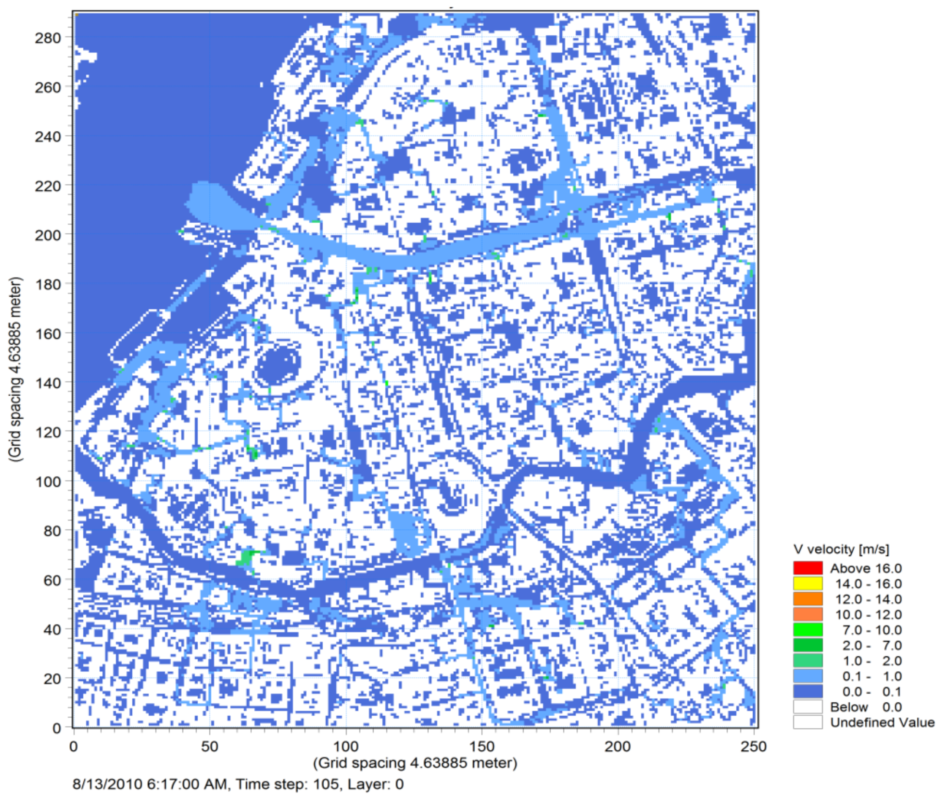

Figure 38 Velocity for flood event in 2010 with constant Manning numbers

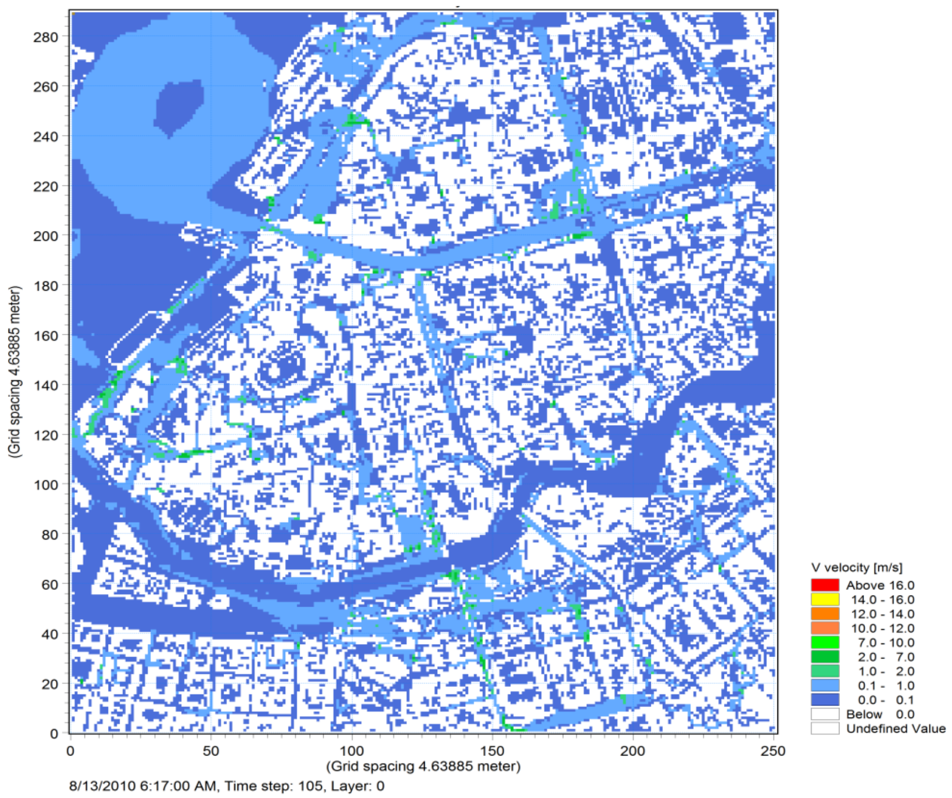

Figure 39 Velocity for flood event in 2010 with distributed Manning numbers

Appendix III Overlay on Google Maps

Figure 40 Rainfall Event in 2010 with Constant Manning Numbers

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