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Vulnerability assessment of urban flooding in Lerum Municipality and study of effectiveness of blue-green mitigation measures using software MIKE 21 and SCALGO Live

Master's thesis in Infrastructure and Environmental Engineering
UTSAV ADHIKARI

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF WATER AND ENVIRONMENT TECHNOLOGY
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Live

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Supervisor: David Hirdman, Lerum Municipality

Supervisor: Ekaterina Sokolova, Architecture and Civil Engineering

Examiner: Mia Bondelind, Architecture and Civil Engineering

Department of Architecture and Civil Engineering

Division of Water and Environment Technology

Chalmers University of Technology

SE-412 96 Göteborg

Sweden

Telephone: + 46 (0)31-772 1000

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Abstract

A much-realized consequence of climate change is shift in precipitation pattern and increase in extreme rainfall events. Moreover, growing urbanization trend associated with population and wealth growth has caused increase in impervious surfaces, while lowering groundwater recharge. In Sweden, the annual precipitation amount is predicted to increase consistently towards the end of this century thus increasing the likelihood of urban flooding risk. Lerum Municipality has realized this consequence of climate change and prepared a flood map for the municipality using a 2D hydrodynamic model to study the urban flooding risks and develop strategies to reduce these risks. In the thesis work, this flood map was utilized to investigate infrastructure vulnerable to flood and to locate areas where risks to human life can arise. Further, this thesis work has also supported the municipality to develop and investigate climate change adaptation strategies to reduce or eliminate urban flooding risk for two study areas – Hulan and Berghultskolan. Using GIS analysis, high flooding risk was obtained for both study areas affecting mostly residential houses and residential streets. Appropriate blue-green measures were proposed to regulate the stormwater runoff in both upstream and downstream areas. The effectiveness of the proposed measures was tested using two computer models - SCALGO Live and MIKE 21, and the results were compared. Similar results were obtained from both models, showing that blue-green measures are very effective in regulating stormwater runoff. Even though flood volume was significantly controlled in the Hulan area, there was still risk of flooding at the downstream point. However, the blue-green solutions proposed in the Berghultskolan area were successful in protecting the area from flooding risk. Sensitivity tests were performed for the proposed solution i) by testing against a more extreme rainfall event and ii) by changing the size of the solution by 10 percent. Uncertainties associated with model calibration, analysis technique and limitations of software were studied. Finally, recommendations for future studies as well as alternative flood mitigation solutions were suggested to the municipality based on the data obtained from the results and their critical analysis performed during the study.

Key words: blue-green solutions, climate change, hydraulic modelling, urban flooding

En sårbarhetsbedömning av översvämningsrisker i Lerum kommun och en studie av effektiviteten av blågröna åtgärder med hjälp av programvarorna MIKE 21 och SCALGO Live

Examensarbete inom masterprogrammet infrastruktur och miljöteknik

UTSAV ADHIKARI

Institutionen för arkitektur och samhällsbyggnadsteknik
Avdelningen för vatten miljö teknik
Chalmers tekniska högskola

SAMMANFATTNING

En konsekvens av klimatförändringar är förändrade nederbördsmonster och ökade antal extrema regnoväder. Vidare, en växande urbaniseringstrend tillsammans med befolkning- och rikedomstillväxt har orsakat ökade ogenomträngliga ytor samtidigt som grundvattnet sänks. I Sverige förväntas den årliga nederbörds mängden öka konsekvent mot slutet av detta århundrade, vilket ökar sannolikheten för översvämningar i städer. Lerums kommun har insett denna konsekvens av klimatförändringarna och tagit fram en översvämningskarta med hjälp av en 2D hydrodynamisk modell för att kunna studera riskerna för översvämning och utveckla strategier för att minska riskerna. I denna studie användes denna översvämningskarta för att undersöka infrastruktur som är sårbar för översvämningar och för att lokalisera områden där risker för människors liv kan uppstå. Denna studie har också bistått kommunen i att utveckla och undersöka anpassningsstrategier för klimatförändringar för att minska eller eliminera översvämningsrisker för två studieområden – Hulan och Berghultskolan. Båda studieområdena hade hög översvämningsrisk som främst påverkar bostadshus och tillhörande gator. Lämpliga blågröna åtgärder föreslogs för att reglera avloppsvattnet i både uppströms- och nedströmsområden. Effektiviteten av de föreslagna åtgärderna testades med hjälp av två datormodeller – SCALGO Live och Mike 21, och resultaten jämfördes. Liknande resultat erhöles från båda modellerna, vilket visade att blågröna åtgärder är mycket effektiva för reglering av avloppsvatten. Trots att översvämningsvolymen kontrollerades betydligt i Hulan fanns fortfarande risk för översvämningar vid nedströmspunkten. De blågröna lösningarna som föreslogs i Berghultskolan-området lyckades emellertid skydda området mot översvämningsrisk. Känslighetstester utfördes för den föreslagna lösningen i) genom testning mot en mer extrem regnhändelse och ii) genom att ändra storleken på lösningen med 10 procent. Osäkerheter associerade med modellkalibrering, analysteknik och programmets begränsningar studerades. Slutligen föreslogs rekommendationer för framtida studier såväl som alternativa lösningar för översvämningsminskning till kommunen baserat på de uppgifter som erhöles från resultaten och deras kritiska analys utförda under studien.

Nyckelord: blågröna lösningar, klimatförändring, hydraulisk modellering, översvämning

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Glossary

100- year rainfall event A rainfall event of that magnitude which has a 1 percent chance of happening in any year.

Blue-green solutions Flood mitigation measures that utilize nature to control urban runoff and which are designed to manage and use rainwater close to where it falls, on the surface and incorporating vegetation.

Catchment area Area from which rainfall flows into a point on land surface.

Critical flood depth A specific depth of water for different infrastructural units surpassing which the associated units are exposed to flood risk.

DEM A Digital Elevation Model is a 3D representation of a terrain's surface where each pixel represents elevation for the area represented by the pixel.

Detention basin Landscape depressions that are normally dry except during and immediately following storm events.

Downstream point Lowest point in the catchment area where water from the entire catchment is concentrated.

Drainage channel Shallow, flat bottomed and vegetated open flow path designed to convey, treat and often attenuate surface water runoff.

Evapotranspiration A collective term to represent a combination of evaporation and transpiration.

Flexible mesh A network of editable irregular triangular and quadrilateral elements where each element represents elevation for the specific geometry.

Flood hotspots Zones that are relatively likely to be exposed to flooding during an extreme rainfall event.

Meanders A series of regular sinuous curves, bends, loops, turns, or windings in the channel of a river, stream, or other watercourse.

Infiltration capacity The maximum rate at which infiltration can occur under specific conditions of soil moisture. For a given soil, the infiltration capacity is a function of the water content.

Land use map A map consisting of vector images of different infrastructural units that represent the potential uses of unit of land.

Manning number A number that represents the roughness or friction applied to the flow by the surface material. Surface with higher Manning number imposes less resistance to flow and vice versa.

Mesh A network of irregular triangular and quadrilateral elements obtained from DEM where each element represents elevation for the specific geometry.

Multilevel stormwater pond Landscape depression that consists of different elevation level designed in such a way that the deeper level is filled first and then the higher level. Deeper level is usually the furthest point from the settlement area.

Overland flow Movement of water over the land, downslope towards a surface water body.

Property map A map consisting of vector images that shows land area owned by person or organization.

Raster image An image generally consisting of rectangular grid of pixel where each pixel stores information of one kind, e.g. elevation.

Vector image An image file with array of geometric shapes like points, line and polygons where each geometric shapes is linked to multiple attributes.

Vulnerability The quality or state of being exposed to the possibility of being harmed by hazards.

Wetlands A wetland is a distinct ecosystem that is flooded by water, either permanently or seasonally, where oxygen-free processes prevail.

1. Introduction

Climate change is a certain future that is surged particularly due to the anthropogenic interference to the climate system (IPCC, 2014). A much realized consequence of the climate change is a shift in precipitation pattern which will increase the frequency and magnitude of extreme rainfall events as well as expedite the risk of flooding (NASA, 2020). The problem associated with increasing precipitation is further intensified in urban areas where impervious paved surface hinder soil infiltration and groundwater recharge (MSB, 2017). As a result, a large share of stormwater volume flows through land surfaces to increase the inland flooding risk in an urban environment. The sources of urban floods and their hazardous consequences are accelerating against the synergy of climate change, demographic growth, and urbanization patterns (Jha et al., 2012). Urban floods, depending upon degree of flow and velocity, has the ability to destroy farmland and critical infrastructure, displace human population, disrupt economic activities, and in the worst cases, lead to epidemic and death (Nkwunonwo et al., 2020) due to inland flooding and groundwater intrusion through basement walls and flooding from drainage system (Sørensen & Mobini, 2017). The study of urban flood in a growing city, its cause and effect, therefore, carries a paramount importance while planning an urban future and create the resiliency to adapt to climate changes.

Green cities recognize connections between different urban sectors and support development strategies that fulfil multiple functions and create multiple benefits for society and urban ecosystems (Brears, 2018). As such, urban planners and politicians face public pressure as well as technical challenges to include climate change adaptation strategies and become resilient against its hazardous consequences (Alves et al., 2020). Common flood mitigation approaches involve usage of heavily engineered structural measures, which are effective but not sustainable since the flood risk is transferred downstream and additionally, these structural measures are often costly and time consuming (Jha et al., 2012). Moreover, erosion and rapidly fluctuating water levels as well as high nutrient and sediment transport are some effects that may be further amplified downstream by structural measures (Jordbruksverket, 2015). This has gathered attention to focus towards the measures that are effective as well as sustainable and at the same time economic, easy to maintain and not requiring intensive construction. A commonly used nature-based solution to tackle urban flooding is the use of so called ‘blue-green solutions’ or ‘blue-green measures’, which manipulate the contributing catchments by introducing retention/detention capacities, and promote sustainable multifunctional initiatives to adapt against climate change (European Commission, 2015). These blue-green solutions, if designed properly can control the quantity of runoff, manage the quality of runoff, and create amenity and biodiversity in a natural way (CIRIA, 2017).

Recent development in computer technology has created the opportunity to predict both magnitude and direction of urban runoff as well as test and compare performance of different flood mitigation measures in a virtual environment. Moreover, results obtained from these different computer-based flood models help to understand problems from different dimensions and provide support to predict the best possible solution at a reasonable cost. Usage of computer models to identify areas vulnerable to flooding events is one of the most effective ways of assessing flood risk to people and properties (Yuan & Qaiser, 2011). At present, some examples of commonly used flood simulation software for studying the behavior of urban runoff are SWMM, MIKE 21, InfoWorks-ICM SCS, HydroCAD, and SCALGO Live (Li et al., 2018).

Swedish Municipalities are increasingly using flood models to study the implementation of flood risk management, climate adaptation strategy and measures, in local level planning and management (Norén et al., 2016). The Swedish Civil Contingencies Agency (Myndigheten för Samhällsskydd och Beredskap, MSB), responsible for issues concerning civil protection, public safety and emergency management has developed a methodology for investigating effects of torrential rainfall on essential services at the municipal level (MSB, 2014) as well as a guidance to municipalities on their way to torrential rain resistant city (MSB, 2017). Both guidelines focus on the preparation and study of the flood map using flood models as a tool to perform flood risk assessment of the municipalities. Major cities in Sweden including Stockholm and Gothenburg have prepared the cities flood map considering different extreme rainfall events. These maps are used by urban planners and decision makers as a basis for decision making and to develop climate change adaptation strategies.

Similarly, Lerum Municipality, in the Western Sweden region, have realized the potential effects of the changing climate and is including climate change adaptation strategy into their municipal plan and future investments with an aim to become climate resilient (Lerum, 2019). To accomplish this goal, the municipality has created a flood map using a computer model i) to identify flood vulnerable infrastructure and public places in different areas of municipalities and ii) to develop and analyze climate change adaptation strategies to reduce urban flooding risk in Lerum Municipality. The flood map has been prepared for current and future land use scenarios for multiple extreme rainfall events (Tyréns, 2019).

1.1. Aim and objectives

The primary aim of the thesis work is to provide decision-support to Lerum Municipality regarding the implementation of climate change adaptation strategies to mitigate the urban flooding risk caused by extreme rainfall events for two study areas. To achieve the aim, the following objectives are:

- to formulate rainfall and land use scenarios.
- to use GIS tools to perform flood vulnerability assessment in study areas to evaluate flood risk to both critical infrastructure and human life.
- to propose appropriate blue-green solutions in study areas.
- to design proposed solutions based on available scientific and engineering references.
- to use two computer models (SCALGO Live and MIKE 21) to study effectiveness of the proposed blue-green solutions against the selected extreme rainfall event.
- to test the resilience of the solution to more extreme rainfall events.

1.2. Limitations of the study

- Only inland flow is considered in the model and the pipeline or drainage capacity is assumed as constant throughout the study area.
- Only solutions feasible for the public areas are included. Blue-green solutions that could be implemented in private areas are not considered.

- The study focuses only on the assessment of quantity of flooded water; water quality considerations are outside the scope of this thesis.
- The precipitation included in the hydraulic model is a representation of a 100-year rainfall event, based on a historical extreme rainfall event.

2. Background

2.1. Climate change, urbanization and urban flooding

Rapid urbanization coupled with climate change is creating a mix of increasingly inextricable challenges (Alexander et al., 2019). Rising global temperatures due to climate change are projected to increase intensities and frequencies of extreme storm events (Steffen et al., 2017). In Sweden, the precipitation amount is predicted to increase during the autumn, winter and spring (Commission on Climate and Vulnerability Sweden, 2007). This includes the Western Sweden region, where the precipitation pattern is predicted to increase throughout the century according to regional climate model RCA4 developed by the Swedish Metrological and Hydrological Institute (SMHI, 2019). Figure 1 below shows the percentage change in annual precipitation amount for the Western Sweden region until the end of the century. Black trendline in the figure shows that the total annual precipitation has gradually increased within the reference interval of 1960-2010 and it is further predicted to increase until the year 2100. The shifting trend in the annual precipitation pattern is predicted to increase the frequency of more extreme rainfall events. These extreme rainfall events are denoted in terms of their return period. For example, a 100-year rainfall event represent a rainfall event of that magnitude which has 1 percent chance of happening in any year.

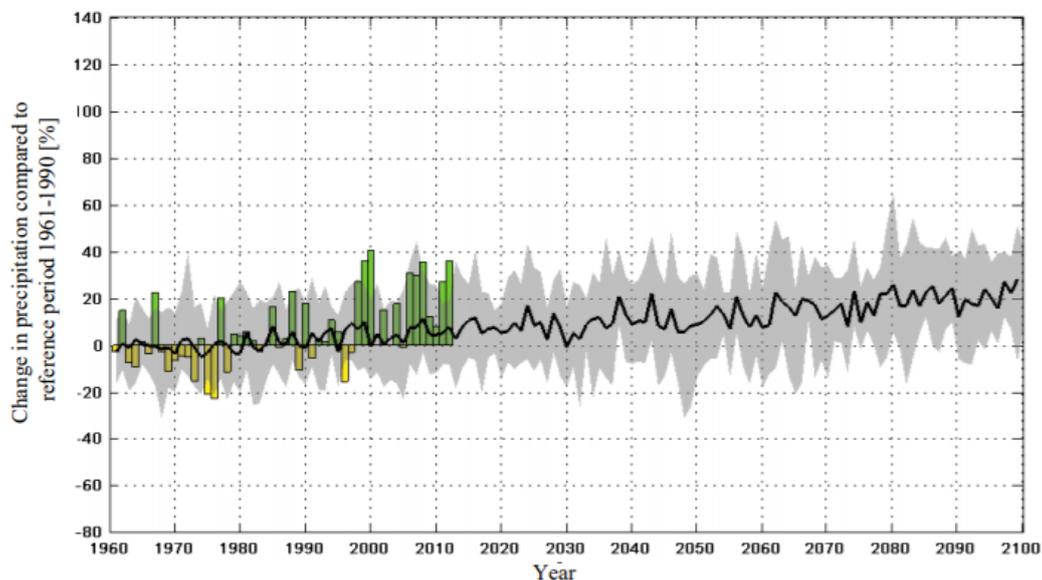


Figure 1 Estimated change in annual precipitation in the County Västra Götaland Län until 2100 in comparison to reference period 1961-1990. (Image Source: SMHI)

Similarly, rapid urbanization leads to an increase in impermeable surfaces such as pavements, roads or roofs in city areas to decrease soil infiltration capacity and ground water recharge. As a result, most water flows through land surface and hence increases the inland flooding risk in an urban environment (Zhang et al., 2017). In Sweden, most people live in urban areas at about 87 % (SCB, 2018), and the country is expanding rapidly especially in the Western Sweden region, which accounts for 15 percent of total land development in the country (SCB, 2015). This growing urbanization trend drive a development of a denser urban space, which is putting a high pressure on urban environment and its stormwater drainage system (Wihlborg et al., 2019).

Climate change, on the one hand, has large impacts on water cycle and extreme precipitation patterns, and can thus directly affect surface runoff and flood frequency and magnitude (Karamouz et al., 2011; Mahmoud and Gan, 2018; Yazdanfar and Sharma, 2015). On the other hand, population growth and rapid urbanization is one of the major causes of increasing impermeable surfaces for flooding in urban areas (Dawson et al., 2009; Huong and Pathirana, 2013; Li et al., 2013; Mahmoud and Gan, 2018). Therefore, with increase in urbanization further exacerbated by climate change, study of flood mitigation measures are becoming more crucial as a form of adaptation to offset the risk of urban flooding.

2.2. Flood modelling software

As mentioned in section 2.1, it is now widely realized that climate change shifts the precipitation pattern leading to an increase in the frequency for extreme rain event and urban floods. This makes the implementation of climate resilient stormwater solutions in urban environment very apparent. The study of flood characteristics, namely flood-upstream and downstream, volume of water collected and flood velocity, thus carries a paramount importance to reduce the urban flooding risk in a sustainable way. Flood modelling using a computer software is a very effective tool to understand cities natural drainage system as well as sewer system (Freni et al., 2010; Eckart et al., 2017). Flood modeling is important in understanding urban water dynamics and reliable for climate impact assessment (Semadeni-davies, 2008). However, development of accurate flood modelling tool to better understand and mitigate increasing urban flood risk has become a global endeavor (UNISDR, 2002). As such, several of these flood models are available, with varying degrees of simplification and applicability; each has its own advantages and disadvantages, particularly in terms of the costs of the software and computer model runtime. Two of these available models, MIKE 21 and SCALGO Live will be used in this study to conduct flood vulnerability assessment as well as to assess the performance of the proposed blue-green solutions. SCALGO Live is a GIS-based web tool used to analyze elevation data from a surface perspective that uses both terrain data and water volumes to identify the areas that are flooded at a given water volume (SCALGO Live, 2019). MIKE 21 on the other hand is a much advanced standalone modeling system by DHI that uses digital elevation model (DEM) of the study area and its hydrological and hydrogeological parameters to model two-dimensional free surface flow for inland and overland flow modeling (DHI, 2011). A detail explanation on the working principle for these models are given below:

2.2.1. SCALGO Live

SCALGO Live is a web-based flood modelling tool that is used to map the flood risk from sea, in depressions or from watercourses to get an overview of the combined flood risk of a property, a neighborhood or an entire municipality (SCALGO Live, 2020). It is used for flash flood mapping, which means it shows the extent of water depth where flooded water accumulates during the chosen rain event. During flood risk analysis SCALGO Live uses both terrain data and water volumes to identify areas that are flooded at a given water volume, the principle shown in Figure 2. The amount of water is first filled in a depression, which upon saturation leads the flow into a low point until it reaches to its threshold level (brown dots), and the water flows to the next low point area. In this way, larger the precipitation that charges the terrain, larger is the catchment area of the downstream point. Similarly, orange marker shows the catchment or the

basin that contributes water to the lowest-lying enclosed area. The SCALGO Live tool calculates the depth of water and the propagation (black curved arrows) at the selected precipitation event considering the total amount of water available at the given depression.

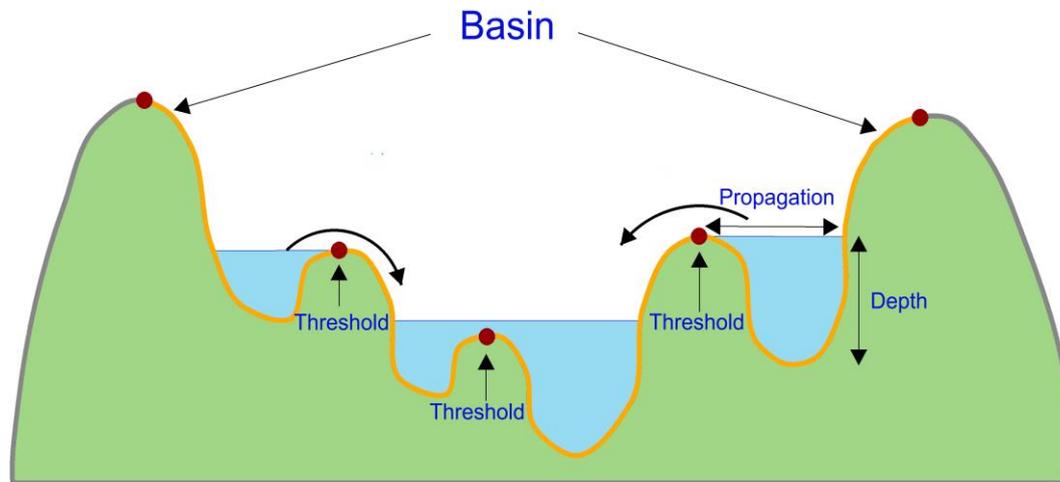


Figure 2 Illustration of flow model in SCALGO Live; Excess flood water after exceeding the threshold point at a depression overflow into the next depression and so on.

Flood analysis process in SCALGO Live gives the amount of water collected at different low points in terrain at different rain events and can therefore be used to identify risk areas at given extreme rainfall events. Moreover, the tool allows to filter the flood depth, so that only water depth that possess serious risk to human and infrastructure can be shown. The method is static, as opposed to the two-dimensional hydraulic modeling techniques traditionally used by torrential mapping. This means that the method lacks the dynamic (time-dependent) aspects, and therefore cannot identify the effects of inertia in the system. Furthermore, SCALGO Live does not feature the effect of soil properties e.g. soil infiltration capacity of the model area, which leads to an overestimation in the flood depth compared to the reality.

2.2.2. MIKE 21 FM

MIKE 21 Flow Model FM is a hydrodynamic modelling system based on a flexible mesh approach developed for applications within oceanographic, coastal and estuarine environments (DHI, 2012). It simulates unsteady two-dimensional flows in one-layer (vertically homogeneous) fluids using the conservation of mass and momentum equation, also known as Saint-Venant equation, integrated over the vertical to describe the flow and water level variations (DHI, 2016). The governing equation for conservation of mass is shown in Equation 1 and that for conservation of momentum in horizontal and vertical directions are shown in Equation 2 and Equation 3 respectively.

Mass Balance Equation:

$$\frac{\partial \xi}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \quad (\text{Equation 1})$$

Conservation of Momentum equation in X-direction:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left(\frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left(\frac{pq}{h} \right) + gh \frac{\partial \xi}{\partial x} + \frac{gp\sqrt{p^2+q^2}}{c^2 h^2} - \frac{1}{\rho_w} \left[\frac{\partial}{\partial x} (h\tau_{xx}) + \frac{\partial}{\partial y} (h\tau_{yy}) \right] - \Omega_q - fVV_x + \frac{h}{\rho_w} \frac{\partial}{\partial x} p_a = 0 \quad (\text{Equation 2})$$

Conservation of Momentum equation in Y-direction:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial y} \left(\frac{p^2}{h} \right) + \frac{\partial}{\partial x} \left(\frac{pq}{h} \right) + gh \frac{\partial \xi}{\partial y} + \frac{gp\sqrt{p^2+q^2}}{c^2 h^2} - \frac{1}{\rho_w} \left[\frac{\partial}{\partial y} (h\tau_{yy}) + \frac{\partial}{\partial x} (h\tau_{xx}) \right] - \Omega_p - fVV_y + \frac{h}{\rho_w} \frac{\partial}{\partial y} p_a = 0 \quad (\text{Equation 3})$$

Where,

$h(x,y,t)$ - water depth = $\xi - d$, m

$d(x,y,t)$ - time varying water depth, m

$\xi(x,y,t)$ - 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 ($\sqrt{m/s}$)

g - acceleration due to gravity (m/s^2)

$f(V)$ – wind friction factor

$V, V_x, V_y(x,y,t)$ – wind speed and components in x- and y- directions (m/s)

$\Omega(x,y)$ – Coriolis parameter, latitude dependednt (s-1)

$p_a(x,y,t)$ – atmospheric pressure (kg/m^2)

ρ_w – density of water (kg/m^3)

x,y – space coordinates (m)

t – time (s)

Equations 2 and 3 above show that the change in water depth is a function of combination change in surface elevation and change in flux densities in x and y directions. The three equations mentioned above are solved by using ADI (Alternating direction implicit) technique integrated in the space-time domain. Scientific theories used to describe the flow behavior in MIKE 21 are explained in the scientific documentation of MIKE 21 (DHI, 2016).

In MIKE 21, the hydrodynamic model consists of a structured/unstructured mesh that represents the topography of the computational domain obtained from DEM (Digital Elevation Models), which in turn is a 3D representation of the terrain in a digital format. DEM is created using GIS software by interpolation of elevation data obtained from field measurement or through high resolution laser scanning of the study area. Other hydro dynamic forces included in the software are spatial and temporal distribution of

hydrographs, soil infiltration capacity, roughness coefficient and domain boundary condition. Finally, using flow equation as mentioned in Equation 2 and 3, the software simulates the flow, considering the given input variable for the specified time scale, and solves them numerically to give output in terms of flood depth and velocity. Results obtained from the model can be used as a basis for flood impact assessments, structure plans and measures and contingency planning.

2.3. Flood map

The use of flood modelling tools as mentioned in section 2.2 facilitate quantitative assessment of different hydrological and geological properties using sophisticated flow theories based on laws of advanced physics, which could be daunting to a non-technical individual. Nevertheless, the result obtained from the computer model can be analyzed in a GIS setting by conducting required spatial analysis (refer to Eximap, 2007) to generate various flood maps which are easy for a general public to understand. Flood maps help to understand and communicate flood severity and characteristics, and thus are considered as the first step to flood risk management (Jha et al., 2012). In fact, The EU Flood Directive (2007/60/EC) requires all member states to assess flood hazard risk and adopt measures to reduce adverse impacts due to flood events, and the key step to the directive is the preparation of flood hazard map (Macchione et al., 2019). According to the handbook on good practices for flood mapping prepared by European exchange circle on flood mapping, Eximap (2007), flood maps are primarily divided into two sub-categories: flood hazard map and flood risk map depending upon its content, purpose of use, accuracy and target user. The flood hazard map shows various flood hazard e.g. flood depth, velocity etc., while the flood risk map shows the degree of vulnerability of the flood hazard to the selected vulnerable units explained in their respective sections.

2.3.1. Flood hazard map

Flood hazard maps are the results of a process that includes hydrological, geospatial and hydrodynamic analyses that show flood parameters such as- (i) level of inundation, (ii) intersection of flood level with terrain (creates flood extent), (iii) flood depth as the difference between flood level and the terrain, and (iv) the distribution of velocity. (Eleutério, 2013). Figure 3 below shows a schematic diagram of flood hazard map.

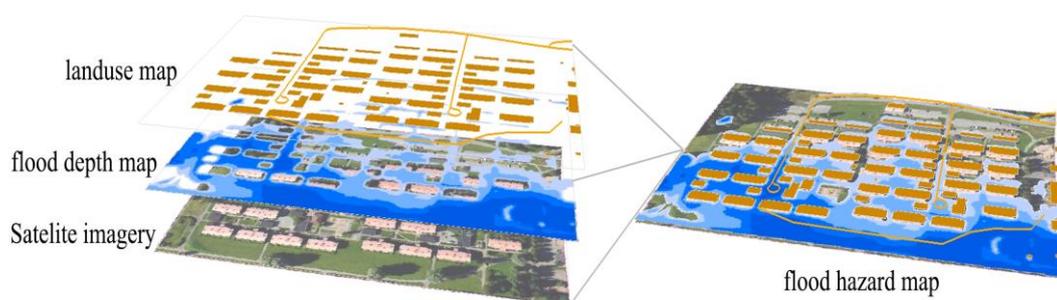


Figure 3 Schematic diagram of flood hazard map obtained after combination and analysis of land use map, map of flood depth extent and google satellite image for a study area.

As can be seen in Figure 3 above, flood hazard map gives the extent and severity of the damage, which can be utilized by national, regional or local land use planning committee, flood managers, forest services or emergency services for different objectives. Eximap (2007) has illustrated following purposes and uses of these maps:

- land use planning and land management;
- catchment management;
- water management planning;
- hazard assessment on local level;
- emergency planning and management;
- planning of technical measures;
- overall awareness building.

2.3.2. Flood risk map

A flood risk map combines various flood parameters to form a risk level or degree (depth, velocity, debris often combined with recurrence interval). Flood risk map refers specifically to information concerning the assets and the public health and their sensitivity to flood water (Budy, 2016). Like flood hazard map, flood risk maps are informative to national, regional or local emergency services as well as governmental authorities for various purposes. Countries in Europe and America have specific guidelines for flood risk assessment. In Sweden, the Swedish Civil Contingency Agency (MSB) recommends to perform a flood risk assessment by preparing a flood risk map for critical infrastructure and for public vulnerability (MSB, 2017). According to Eximap (2007), flood risk maps have following advantages:

- basis for policy dialogue;
- priority setting for measures;
- flood risk management strategy (prevention, mitigation);
- emergency management (e.g. the determination of main assets);
- overall awareness building.

2.4. Urban stormwater system and blue-green solutions

Quantitative assessment of flood is made using the flood models to understand the source and sink of urban floods as mentioned in section 2.2 followed by preparation of flood maps to study the flood hazard and the risk associated with the hazard as mentioned in section 2.3. The next step would be to implement the solutions to mitigate the flood risk. But before the flood controlling measures are implemented, it is important to understand the urban stormwater network system: its operation, capacity and limitations. This will provide the required technical assistance during a feasibility study to identify the best possible solution. Traditionally, stormwater systems are built using structural measures such as stormwater drainpipes, curb inlets, manholes, minor channels, roadside ditches, and culverts to divert stormwater from locations as quickly as possible (Brears, 2018). Urban drainage network consists of two types of sewer system: combined and separate. In a combined system, wastewater and stormwater are collected in one pipe network, while in a separate system, each unit has its own network. A schematic view of the two sewer system types is shown in the Figure 4 below, which shows the operation of the two stormwater network systems.

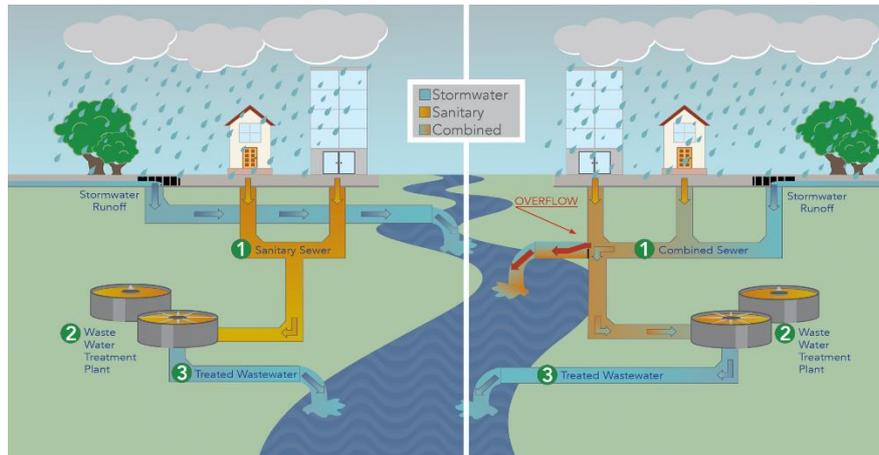


Figure 4 Schematic diagram of combined and separate sewer systems. (Image source: Nspiregreen, 2019)

Although conventional structural stormwater network systems have proven successful over many decades in capturing and draining stormwater runoff from the flood region, relying on them has resulted in numerous unintended negative consequences in terms of water quantity and quality (Zhang et al., 2017). For example, these network of structural solutions designed to prevent localized flooding resulted in downstream flood threats as well as stormwater overflows into waterways (Jha et al., 2012). At the same time, these structural solutions have impacted the local hydrological cycle with less groundwater runoff and a lower waterway baseflow, affecting the quality of water (Rodríguez et al., 2018). Moreover, they are unable to deal with extreme weather events related to climate change, with drainage system unable to cope with unexpected, large amount of precipitation (Qiao et al., 2020; Zhang et al., 2017).

In contrast, blue-green solutions is an umbrella term for sustainable multifunctional measures able to reduce negative effects of urbanization and adapt to a changing climate (Wihlborg et al., 2019). Blue-green solutions support stormwater systems by allowing the passage of runoff to avoid flooding and consequential damage to public and private properties while also treating stormwater. The main goals of blue-green solutions are : (1) preserving or enhancing the natural, social and economic values of downstream environments; (2) reducing the frequency, length and amount of stormwater runoff to reduce flood hazards and limit post-development flows into waterways and (3) improving urban environment amenities (Brears, 2018). Moreover, integrating the features of blue green solution into the process of infrastructure design as a retrofit, especially in dense urban areas, redirects runoff to the pervious areas instead of sewers (Naeimi and Safavi, 2019).

Blue green solution is the combination of LID (Low impact Development) and BMP (Best Management Practices) to control urban runoff in the most natural manner (Naeimi and Safavi, 2019). LID is a general site design that decentralizes stormwater management and controls the stormwater as close to the source as possible. This includes solutions such as green roofs, rain barrels, permeable pavement etc. which possess smaller water retention capacities since they can be easily implemented in a limited available space. On the other hand, BMP is a much larger unit that is built with an intention of massive water storage beneficial for intensive and long-term events. Some examples of BMPs are stormwater ponds, large retention basins, detention basins etc. The umbrella term ‘blue-green solutions’ is extensively used since the combination

of LID and BMP compliments each other to control urban flood as well as to achieve sustainable urban stormwater management. Blue-green solution is a commonly known term in Germany and the Scandinavian countries. Other terms used elsewhere with similar objectives are Green infrastructure in the US, Sustainable Urban Design System (SUDS) in the UK, Water Sensitive Urban Design (WSUD) in Australia and Nature based solution in Asia (CIRIA, 2017; Sydney Water, 2018).

2.5. Assessment of blue-green solutions using computer-based flood models

References cited in the literature review are listed in Table 1. Information on blue-green measures used, study area, hydraulic model type, runoff reduction, peak flow reduction are also provided. Different computer models with distinct functionalities and model properties depending upon the study purpose have been widely used to model the performance of blue-green measures. (Xiao et al., 2007) used a self-made numerical model to evaluate performance of a tree garden in a residential area in Lon Angeles and found that increased groundwater infiltration played a greater role than evapotranspiration. The study suggested that caution should be taken not to contaminate groundwater in areas with highly permeable soil as runoff is collected from paved surfaces. Similarly, (Qin, Li, & Fu, 2013) used Stormwater Management Model (SWMM) to evaluate performance of different blue-green measures at a catchment level and found out that swales were not successful at reducing flood volumes because they received runoff from too wide of an area and were easily overflowed. But they also found that permeable pavement and green roofs were effective at reducing flood volumes for precipitation events between 70 and 140 mm. In an another study with SWMM model by (Palla & Gnecco, 2015) they studied the impacts of blue-green measures at a catchment level in a general urban area and concluded that hydrological efficiency was linearly dependent on successful impermeable area reduction and a reduction of greater than 5 percent was needed to achieve significant benefits. The study found improvements in hydrological value were driven by the blue-green measures retention capacity.

Table 1 Hydrological performance of blue-green measures in simulation using different flood modelling software

| Blue-green measures selected | Study area | Model | Runoff/outflow reduction | Peak flow reduction | Source |
|--|------------------------------------|----------------|---|----------------------------|-----------------------------|
| Decrease impervious area, rain barrels, routing to pervious, bioretention cells, increased storage. | Beijing Olympic Village, China; | SWMM, BMPDSS | 27% | 21% | (Jia, Lu, Yu, & Chen, 2012) |
| Permeable pavement, green roofs | Birmingham, U.K., industrial area; | SUDSLOC, STORM | 57% (30-year rainfall event) 30% (200-year rainfall event) | NA | (Ellis & Viavattene, 2014) |
| Infiltration basins to disconnect impervious areas | Coventry, U.K., residential area; | SUDSLOC, STORM | 95% (30-year rainfall event) 55% (200-year rainfall event) | NA | (Ellis & Viavattene, 2014) |

| | | | | | |
|--|--|----------------|---|---|---------------------------|
| Differences in development density and impervious area | South Weymouth Naval Air Station, U.S.; | SGWATER | 20% to 38% | NA | (Pyke et al., 2011) |
| Rainwater harvesting, permeable pavement and bioretention | Bronx River Catchment, U.S. | SWMM | 28% (2-year rainfall event) 14% (50-year rainfall event) | 8% to 13% | (Zahmatkesh et al., 2015) |
| Dry swales, bioretention, rain barrels, and green roofs | Village at Tom's Creek, U.S.; | SWMM | 59.1% (unfavorable conditions for both LID and conventional) 83.5% (favorable) | LID outperformed conventional for up to 100 y storms. | (Bosley & Kern, 2008) |
| Green roofs (14% of area), bioretention (5% of area) | Singapore Marina Catchment; | MIKE SHE | 30% to 50% (green roofs) 10% increase in infiltration | Delay of 2 h (green roofs) | (Trinh & Chui, 2013) |
| Bioretention (Mel and Bris), permeable pavement (Auk, Scot) | Melbourne, Brisbane, Auckland, Scotland; | MUSIC | 59.5% (Melbourne) 30.4% (Brisbane) 92.9% (Auckland) 100% (Scotland) | NA | (Imteaz et al., 2013) |
| Rain barrels and porous pavement | Urbanized catchment, Indianapolis, U.S.; | L-THIA-LID | 3% to 11% (catchment-wide reduction) | NA | (Ahiablame., 2013) |
| Green channel cover (modeled using bioretention LID) | Bukit Timah catchment, Singapore; | SWMM | Effective in mitigating Runoff | Peak water level 14%, max outflow 21% | (Palanisamy & Chui, 2015) |
| Tree planting | Residential Los Angeles, California; | self-developed | Reduction after 15 years, 26% by year 30 | NA | (Xiao et al., 2007) |

In a more recent study, Liu et al. (2016) used Soil Conservation Service (SCS) model by simulating runoff-generating processes at different rainfall frequencies in Trail Creek catchment located in northwest Indiana to evaluate the hydrological effects of typical blue-green measures and found out that the measures played a significant role in runoff reduction and increasing baseflow. Similar studies using a different software, MIKE SHE by (Trinh and Chui, 2013) in Marina catchment, Singapore was conducted to study the importance of evapotranspiration and groundwater in the hydrological systems. This study found out that distributed blue-green solutions steps may be used with careful planning and design to reshape the outlet hydrograph to an urban catchment.

Different studies have been performed to evaluate the performance of blue-green solutions for centralized and decentralized sewer system. Starting from Brander et al. (2005) which used National Resources Conservation Service (SCS CN) model to compare traditional curvilinear, urban cluster, coving and modern methods of urban planning with and without blue-green measures interventions and concluded that these measures are the most effective for reducing runoff. Semadeni-davies (2008) in a different study using Model of Urban Sewers (MOUSE) in Helsingborg-Sweden modeled the rainfall event in combination with the sewer system and tested the performance of blue-green measures. The study concluded that using blue-green measures as well as disconnecting stormwater from combined sewers could limit or eliminate combined sewer overflows (CSO) under future climate scenarios. Freni et al.

(2010) on the other hand, using self-made model performing similar study in Parco d'Orlèans, Italy found out that storage tanks linked to centralized networks reduced the amount of CSOs and pollutant loads. Stovin et al. (2012) concluded that large-scale disconnection was expensive and difficult to enforce, and indicated that the blue-green measures could better serve as a method for use in tandem with centralized sewage systems

Blue-green measures have been widely adopted and proven successful in many cases; however, there remains uncertainty of its benefits. This thesis work examines the performance of selected blue-green measures to reduce urban flooding during intense precipitation event by using two flood modelling tools MIKE 21 and SCALGO Live.

3. Methodology

3.1. Data collection

The first step of the study was to collect data and information required for the thesis work. The MIKE 21 model files were provided by the consulting company Tyréns AB. Details on values of different parameters used to setup the MIKE 21 model is explained in section 3.4. Other data files that were used in the thesis is presented in Table 2 which also illustrates their source and objectives. Field visit was also conducted to obtain real time data on site condition.

Table 2 Collected data for the thesis work

| S.N. | Type of data | Source | Objective |
|------|---|---|--|
| 1 | MIKE 21 model data | Tyréns AB | <ul style="list-style-type: none">- To study flood characteristics- To prepare flood hazard map and flood risk map |
| 2 | Municipal land use map | Lerum Municipality | <ul style="list-style-type: none">- To identify flood prone critical infrastructure- To overlay in MIKE 21 and SCALGO Live to make a precise assessment |
| 3 | Municipal property map | Lerum Municipality | <ul style="list-style-type: none">- To identify land area that can be used for different blue-green solutions |
| 4 | Swedish governmental publications on flood map preparation, case study report on blue-green solutions | Lerum municipality / institutions' webpages | <ul style="list-style-type: none">- To gain knowledge on the proposed solutions- To provide guidance while designing the proposed solutions |
| 5 | Stormwater manuals, engineering handbooks | Governmental institutions' webpages | <ul style="list-style-type: none">- To gain knowledge on the proposed solutions- To provide guidance while designing |
| 6 | Scientific journals, scholarly articles, books, reports etc. | Chalmers library | <ul style="list-style-type: none">- References in different sections |

3.2. Selection of extreme rainfall event, land use scenarios and study areas

Lerum municipality has prepared flood maps for a majority of the municipal region through hydrodynamic flood modelling technique using MIKE 21 software. The maps are produced for extreme rainfall events with different return periods: 100, 200, 400 and 1000 years. Similarly, the model is prepared for both present and future land use scenarios. Due to limited time constraints of the thesis work, one scenario for rainfall event and one scenario for land use is selected. A 100-year rainfall event was selected in reference to recommendation from MSB (2017), and present land use was selected due to uncertainty in the future developmental process. Hulan and Berghultskolan

region was selected as case study areas after discussions with the municipality. To study flood characteristics in both upstream and downstream areas and to utilize feasible land space as much as possible, the study area was chosen as the catchment area for the downstream point of the two study areas (see Figure 5). The downstream point and its catchment area were found using the catchment tool in SCALGO Live.

3.3. Study area

Lerum municipality lies in Västra Götaland county in Sweden. The first study area Hulan is in the southwestern part of the municipality while the second area Berghultskolan is slightly east from central Lerum (see Figure 5). A brief description of the two-study areas is given below.

3.3.1. Hulan

The study area Hulan lies in southwest of Lerum opposite to lake Aspen (see Figure 5). It is one of the more densely populated areas in Lerum Municipality with mostly residential buildings. The area includes supermarkets, a school to the west and commercial complexes. The total catchment area is about 2.98 km² where approximately 0.38 km² is owned by the municipality. The study area includes 1429 buildings and 21 km road in total. Constructional activities are undergoing in the western part. The study area has a steep terrain toward the central part starting from the eastern and western part creating a valley like formation. A terrain model of the area is shown in Figure A1, Appendix A in terms of a mesh file. In Hulan study area, the downstream point is located next to a dense settlement region and thus there exists very low possibility to contain flood risk in the downstream point. Further, the area is expanding in the future with addition of more residential houses. It further increases the magnitude of urban flooding risk in the Hulan study area. This makes Hulan region an interesting area to study an effect of climate change and formulate strategies to minimize its effect.

3.3.2. Berghultskolan

The study area Berghultskolan is in central Lerum and starts about 400 m from the E20 highway. The area is sparsely populated compared to Hulan study area and contains evenly spread detached houses. Most of the area is covered by forest. There are 259 buildings and 4.38 km road in total. The topography of the area drops from north to west with the lowest point lying next to the school 'Berghultskolan' (see Figure A1, Appendix A). The catchment area is 0.78 km² out of which about 77% is owned by the municipality. Berghultskolan region is already experiencing higher water depth related issues in some lower regions in the area during a heavy rainfall event. Complaints from nearby residents have been registered at the municipality and thus politicians and municipal planners are working to formulate strategies to protect the area from the flooding risk. Furthermore, the school area is undergoing renovation to upgrade their capacity to mitigate flood risk and to accommodate more school children. Proposed flood reduction measures have higher practical implications to support the decision makers in the school area during their expansion campaign. This makes Berghultskolan region an interesting area to study an effect of climate change and formulate strategies to minimize its effect. A major advantage in this area is that higher proportion of land area is owned by the municipality in both upstream and downstream region. Hence, proposed solutions could be implemented with higher ease and less restrictions.

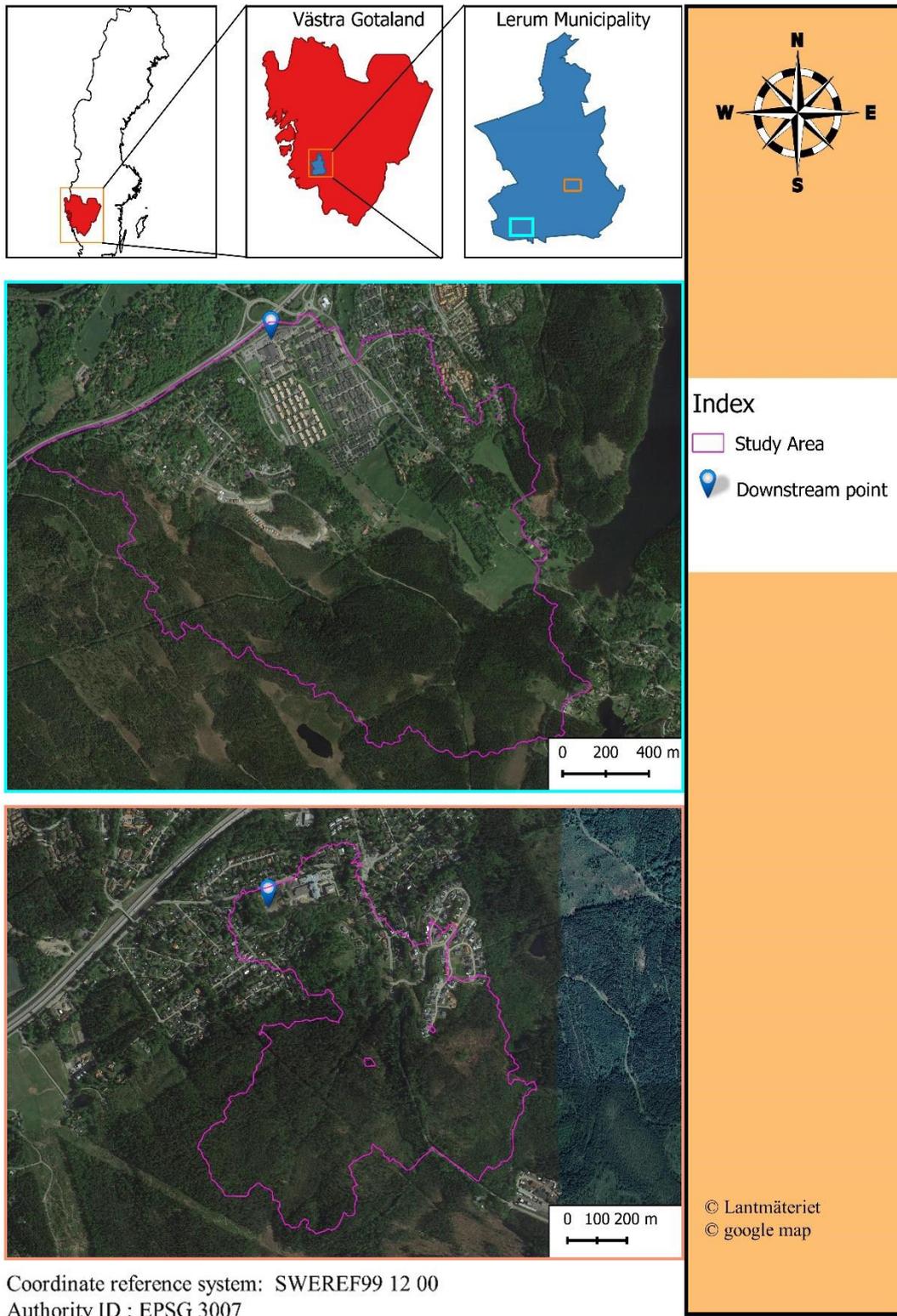


Figure 5 The two study areas for the thesis work. The highlighted area in the map of the Lerum municipality shows the location of the two study areas (top: Hulan and bottom: Berghultskolan); lowest point is marked with blue marker and the boundary area is marked in pink.

3.4. MIKE 21 model setup

The MIKE 21 model was developed by the consulting company Tyréns AB for Lerum municipality. A detail explanation of the model can be found in the report (Tyréns, 2019). The model is briefly described below for the selected rainfall and land use scenario.

In the model by Tyréns, the model area was divided into a total of 13 sub models to decrease the simulation time. Hulan falls in the sub model Lerum southwest and Berghultskolan falls in the model Floda south. The terrain model, used in the software, was based on high resolution laser scanning. The terrain model builds on a flexible computational mesh. Similarly, mapping of hard surface was done by an image analysis where infrared view of the municipality from the year 2018 was used to identify the green surfaces in the area. Hard surfaces that contribute to low flow resistance and high flow such as roof, road, industrial area, parking area were described by Manning's number 50 while green surfaces, for example lawns, ditches etc. were described by Manning's number of 2. This is in accordance to recommendation from MSB (2014). Similarly, the stormwater network capacity of the area was assumed to handle the rain with return period of 2 years during model setup. Soil properties describe the infiltration process and infiltration capacity of the permeable upper layer of soil. For permeable layer an infiltration rate of 36 mm/hr., a soil layer thickness 0.3 m, a porosity of 0.4 and an initial water content 30% were used in the model. The infiltration rate is divided into different soil classes based on a soil map developed by Sveriges Geologiska Undersökning (SGU). For example, soil, gravel and moraine have higher infiltration values of 36 mm/hr. while mud and silt have a lower infiltration value of 0.4 mm/hr. and the bedrock had an infiltration flow of 0.04 mm/hr.

Rainfall patterns in the model by Tyréns builds on a CDS (Chicago Design Storm) model for four rainfall return periods: 100, 200, 400 and 1000 years (see Table 3). The duration was set to 6 hours (9 am to 3 pm) with 10 minutes of peak discharge between 11:15 and 11:25 am. Climate factor, which represents proportional increase in precipitation in future due to climate change, of 1.4 was used in reference to the guideline recommended by SMHI (2015).

Table 3 Total accumulated rainfall volume in 6 hours of rain for return periods 2, 100, 400 and 1000 years which includes a climate factor of 1.4 that was used by Tyréns to run the MIKE 21 model

| Rainfall | Rainfall return period | | | |
|--|------------------------|-----------|-----------|-----------|
| | 2 years | 100 years | 400 years | 500 years |
| Rainfall during 6 h (mm) | 26.1 | 84.5 | 131.7 | 177.1 |
| Climate compensated rainfall over 6 hours (mm) | | 118.3 | 184.3 | 248.0 |

The results from the MIKE 21 simulation performed by Tyréns consulting company is shown in Figure 6.

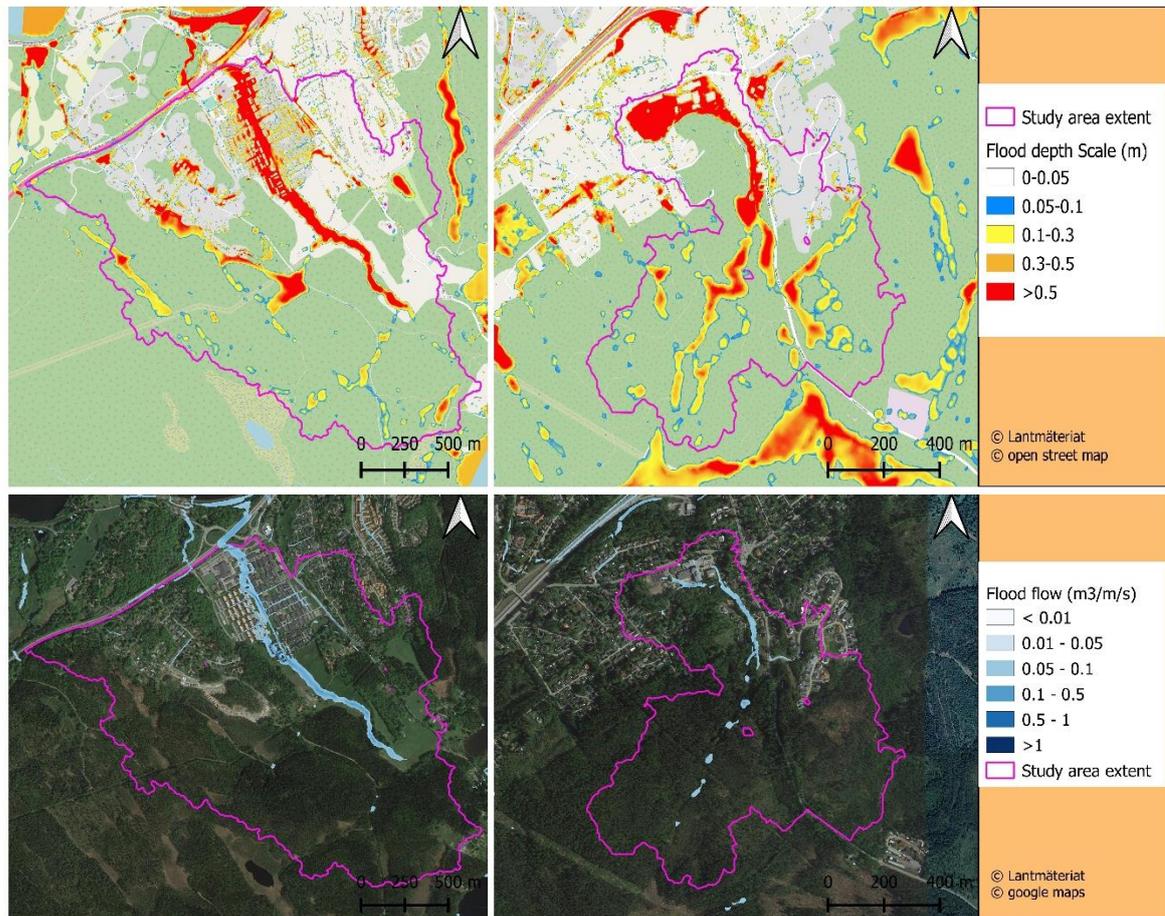


Figure 6 Spatial distribution of maximum water depth (top) and flow (bottom) obtained from the MIKE 21 model for the two study areas Hulan (left) and Berghultskolan (right) for the 100 year rainfall event

3.5. Flood vulnerability assessment

The second objective of the thesis work was to perform flood vulnerability assessment of the selected rainfall and land use scenarios. To fulfill this objective, the output obtained from MIKE 21 simulation result (spatial extent of max flood depth and flow) was imported in Arc-GIS. Spatial analysis tools such as raster extraction, map algebra, raster conversion was used to create a flood extension map in a vector image format that shows flood area greater than critical flood depth. The output from the spatial analysis was intersected with the land use map to identify the flood vulnerable unit. Figure 7 show the schematic of the processes carried out in sequential order. MSB (2017) recommends performing vulnerability assessment to the critical infrastructure (section 3.5.1.) and human life (section 3.5.2.). The assessment was performed for a 100-year rainfall event for the selected land use scenario.

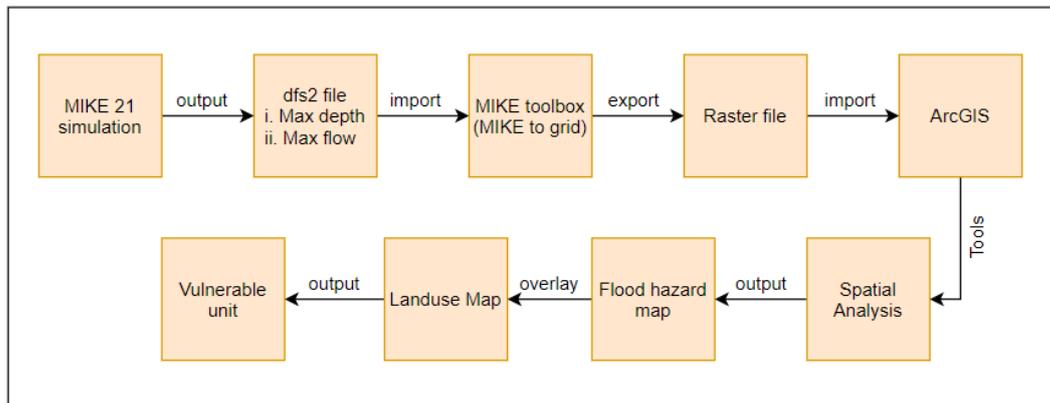


Figure 7 Schematic diagram for the vulnerability assessment. The result from MIKE 21 was first converted to ArcGIS suitable input file and then imported to ArcGIS where spatial analyses were performed to obtain flood hazard map which in turn was overlaid over the land use map to finally obtain the vulnerable unit.

3.5.1. Critical infrastructure

Critical infrastructure are assets that are essential for the functioning of a society and economy. This includes buildings, roads and emergency services such as ambulance, fire trucks, police, highway, high power transmission lines etc. The two study areas include residential, commercial and industrial buildings as well as highways, motorways and residential street. No essential infrastructure like high power transmission lines, police station, fire stations or telecommunication stations are present in the site. Vulnerable buildings and roads in the two-study areas were identified.

Damage to the buildings is mainly due to water depth as the flow is less significant than depth (Jha et al., 2012). Different flood map guideline use 0.1 m as the critical depth that trigger basement flooding in a building (Jha et al., 2012)(MSB, 2017)(Eximap, 2007). Hence, buildings in the study area that were vulnerable to flood depth of more than 0.1 m were identified. Similarly, critical flood depth of 0.15 m and 0.2 m was also used to identify buildings that under higher flood depth risk. Table A3, Appendix A shows the step wise process of spatial analysis performed to obtain the vulnerable buildings.

The effect of urban flood on the functioning of the transportation system vary significantly with rising flood depth. Like buildings, the flow plays less significant role than water depth in roads and hence it was omitted. Flood depth of 0.3 m was taken as a reference while preparing flood risk map since it causes more significant impact on transportation system (Eximap, 2007). Road parts exceeding 0.3 m depth was identified using spatial analysis tool in ArcGIS. Finally, MIKE 21 plot composer tool was utilized to plot the temporal distribution of flood depth in vulnerable road parts.

3.5.2. Public spaces

Urban flood directly or indirectly affects human life. Unlike critical infrastructure, humans are affected by both flood depth and velocity. According to the UK environmental agency (Defra & Environment Agency, 2006), the flood vulnerability to human life is given by Equation 4.

$$V = (v + 0.5) D \quad (\text{Equation 4})$$

Where

V = vulnerability score

v = velocity

D = flood depth

A flood risk map was calculated using Equation 4 by combining the raster map of flood depth and velocity in ArcGIS. The obtained flood risk map was categorized into different risk class according to Table A2, Appendix A. This resulted in a map which showed spatial extent of degree of vulnerability caused by urban flood to human life.

3.6. Selection and design of blue-green solutions

This section explains the blue-green measures selection processes, the selected measures and their proposed designs for the two-study areas. First, the MIKE 21 result files obtained from the consulting company Tyréns was sorted for the 100-year rainfall event and present land use scenario. The sorted result files were studied, focusing on the two study areas, for the spatial and temporal distribution of flooding water depth and the corresponding flow direction over time. This was followed by analysis of magnitude and direction of flow in both upstream and downstream area. Following on, zones that are relatively likely to be exposed to flooding was termed as ‘flood hotspots’. These flood hotspots zones were identified for the two study areas which was also shared with the municipality to obtain valuable updates and feedbacks. Plot composer tool in MIKE 21 was then used to estimate volume of water stored in flood hotspots zones and volume of excess water continuing further downstream. Then, pathway of flood hotspots zones to the downstream point was traced using aerial images. This helped to create a simplified schematic figure of flood pathway for the study areas.

The next process was to organize a physical meeting with Lerum Municipality to identify locations that could be utilized to implement blue-green solutions. In the meeting, critical analysis mentioned above involving flood hotspots and schematic diagram of flood path for two study areas was presented and then discussed with municipality personnel. This was followed by discussion on best possible blue-green solutions for the two study areas. Our first target was to identify solutions in the areas possibly near to flood hotspots zones and owned by the municipality as much as possible to reduce cost of land purchase as well as to limit legality issues. Hence, a layer of a map showing municipal owned property was placed on top of the flood map in Arc-GIS to locate the potential areas that could be utilized to implement blue-green solutions. Since municipal owned properties were not present next to all flood hotspots zones, experts from climate change adaptation strategy unit, environmental protection unit and water and sewage (VA) unit were consulted during the meeting to solve this issue as well as to incorporate local insight to solving the flooding problem. Possible solutions that could be implemented to mitigate flood risk in both the areas in the upstream and downstream areas were discussed. In order to study feasibility of the proposed solutions, it was also decided to arrange a physical site visit. Following on, a field visit was performed together with representatives from the municipality.

During the field visit, each flood hotspot zones were visited to study areas topography, existing human settlement, future infrastructure development, critical infrastructure present in the site and location of flood upstream and downstream. Moreover, elevation measurement was taken at the proposed solution areas to collect data on terrain

adjustment needed. Finally, blue-green solutions that were adjudged most appropriate for flood hotspots zones in both study areas were proposed after the field visit.

This was followed by design of the proposed solutions which was designed according to stormwater manuals and governmental guidelines. Location and extent of the proposed solutions were chosen in discussion with the municipality. Dimension for all proposed solutions are shown in Table A4, Appendix A which provides detail on dimensions of each solution and further contains information on volume of excavation required, volume of filling material required and the design capacity of solutions. Design parameter including slope of the ponds was taken reference from CIRIA (2017), appropriate length to width ratio, maximum depth etc. was taken from Svenskt Vatten (2016). The challenging part while designing solutions was during a design of the flood meander in zone five. Meandering parameters including meandering bend, wavelength, arclength were designed according to an engineering handbook developed by the US Department of Agriculture USDA (2007) and the detailed calculations are shown in Appendix B. MATLAB was used to solve the equation and the result was generated in the form of a sine wave shown in Appendix B. The obtained sinewave is the planform for the meander i.e. its flow path. Similar flow path was then created in the form of a vector image in ArcGIS so that it could be imported into SCALGO Live and MIKE 21 to use it as a reference and create consistency between the two models.

3.7. Preassessment in SCALGO Live

A preassessment for the proposed solutions were performed in the tool SCALGO Live. First, downstream point for both the study areas was located using the flow accumulation tool. Rainfall corresponding to 100-year rainfall event was defined by adjusting the rainfall slider option. To make rainfall consistent to that of MIKE 21, similar accumulated rainfall amount that was utilized while setting up MIKE 21 by Tyréns AB was formulated for SCALGO Live. Total accumulated rainfall amount for 100-year, 400-year and 1000-year rainfall event is shown in Table 3 in section 3.4. Likewise, a rainfall amount corresponding to 2-year return period was deducted to account as an estimation of the stormwater drainage network according to recommendation from MSB (2017) and to make rain volume consistent to that with MIKE 21. Catchment area to the downstream point during the 100-year rainfall event was then found using the watershed tool. A separate workspace was then created for each study areas to an extent corresponding to the catchment area, which produced a separate editable terrain model. Shape files for extent and locations of proposed solution for both the study areas was imported into their respective workspaces. Similarly, in the workspace, proposed solutions were created using suitable terrain editing features in their respective location according to their design. For instance, to maintain consistent longitudinal slope, interpolation tool was used for the given width. Similarly, for designing detention ponds and canals, the 'lower path and flatten' tool was used to lower the terrain from the lowest point and then level at the specified depth. The lower path and flatten tool also contained the feature to create a side slope, which was used to create a slope as designed. The flood meandering solution involved twisting and turning as well as intensive excavation and filling and therefore, was the most challenging of all the measures selected to implement in SCALGO Live model. For this purpose, the shapefile of the planform that was utilized as a reference location and the terrain was edited according to the design proposed. In different locations, filling material was also

added to level the terrain as well as to ease the flow path. SCALGO Live also contains different tools to facilitate these processes. Volume of filling material as well as excavation volume for each solution was calculated separately and it is shown in Table A4, Appendix A.

3.8. Assessment in MIKE 21

Next step of the thesis work was to define the proposed solutions in MIKE 21 which was carried out in mesh files of the two-study area. This section was the most challenging and intensive part of the thesis work. To maintain consistent location for the solutions in the two software MIKE 21 and SCALGO Live, a common shape file was imported into the mesh file. Side slope of the proposed solutions were maintained by manually entering the different elevation value in regular mesh interval. After updating the mesh file for the study areas, the MIKE 21 model was setup. The same time interval of 6 hours was used for the pre-existing precipitation, roughness coefficient and soil model files. Inland flooding option was checked with drying depth of 0.008 m and wetting depth 0.02 m. No changes were made to other parameters which was obtained initially from the consulting company. Output was generated for maximum water depth, maximum flow and area series file on depth.

4. Results

4.1. Vulnerability of study areas to urban flooding

MIKE 21 output files obtained from consulting company Tyréns AB were imported in the GIS environment and then different spatial analyses as mentioned in section 3.5 were performed to carry out flood vulnerability assessment. The assessment was performed for a 100-year rainfall event for the present land use scenario. In the following section, critical infrastructure and public areas under flooding risk during the extreme rainfall event are shown.

4.1.1. Critical infrastructure

Figure 8 below is a flood risk map which shows infrastructure (roads and buildings) that are under urban flooding risk for both study areas – Hulan and Berghultskolan. Buildings are classified into three categories in terms of flood depth: 0.1, 0.15 and 0.2 m. These include general buildings; namely residential, commercial and industrial. In Hulan, large number of buildings were assessed to be vulnerable to flood. In fact, 604 out of 1377 buildings are under risk for 0.1 m flood depth, 377 for 0.15 m, and 248 for 0.2 m. In Berghultskolan study area, out of 150 buildings in the study area, 74, 46 and 34 were found vulnerable under the three flood depth categories respectively.

In Figure 8, dark blue line segment shows the part of the road where the flood depth exceeds 0.3 m. The orange line segment, on the other hand, shows the total road section where there is difficulty in navigation during the extreme rainfall event. In Hulan study area, 29 different road sections were found vulnerable and hence inaccessible, out of which 1.1 km road contained flood depth higher than 0.3 m. Similarly, in Berghultskolan study area, 6 sections, comprising a total of 0.3 km, were affected with flood depth more than 0.3 m. These are mostly residential streets where low traffic volume is expected. However, a section of a major highway was also found vulnerable in the Hulan study area.

A detailed analysis on flood affected road sections was performed to identify duration of flooding risk. Different points were selected in the road section as shown in Figure 8, to study temporal variation of flood depth at those points. Point 6 in the Hulan study area shows the highest flood depth exceeding 1.5 m and it maintains high depth throughout the simulation period. Points 2, 3 and 4 have their respective highest flood depths close to 0.7 m during the peak flow. The graph also shows that the flood depth is over the critical limit of 0.3 m by the end of simulation for these four points. Point 5 has a higher flood depth of over 1 m but decreases sharply immediately after the peak flow ceases. Roads in Berghultskolan study area are less affected by flood than in Hulan study area. Water depth decreases significantly to an acceptable limit after the peak flow ceases. Three points were selected to study temporal variation of flood depth, and it was found that maximum depth at the three points were 0.7 m, 0.4 m and 0.7 m respectively, but in all these three points, water depth decreases significantly as the peak flow ceases. Flood depth at point 3 was well below the critical limit while in points 1 and 2 it was just under the critical limit towards the end of the simulation.

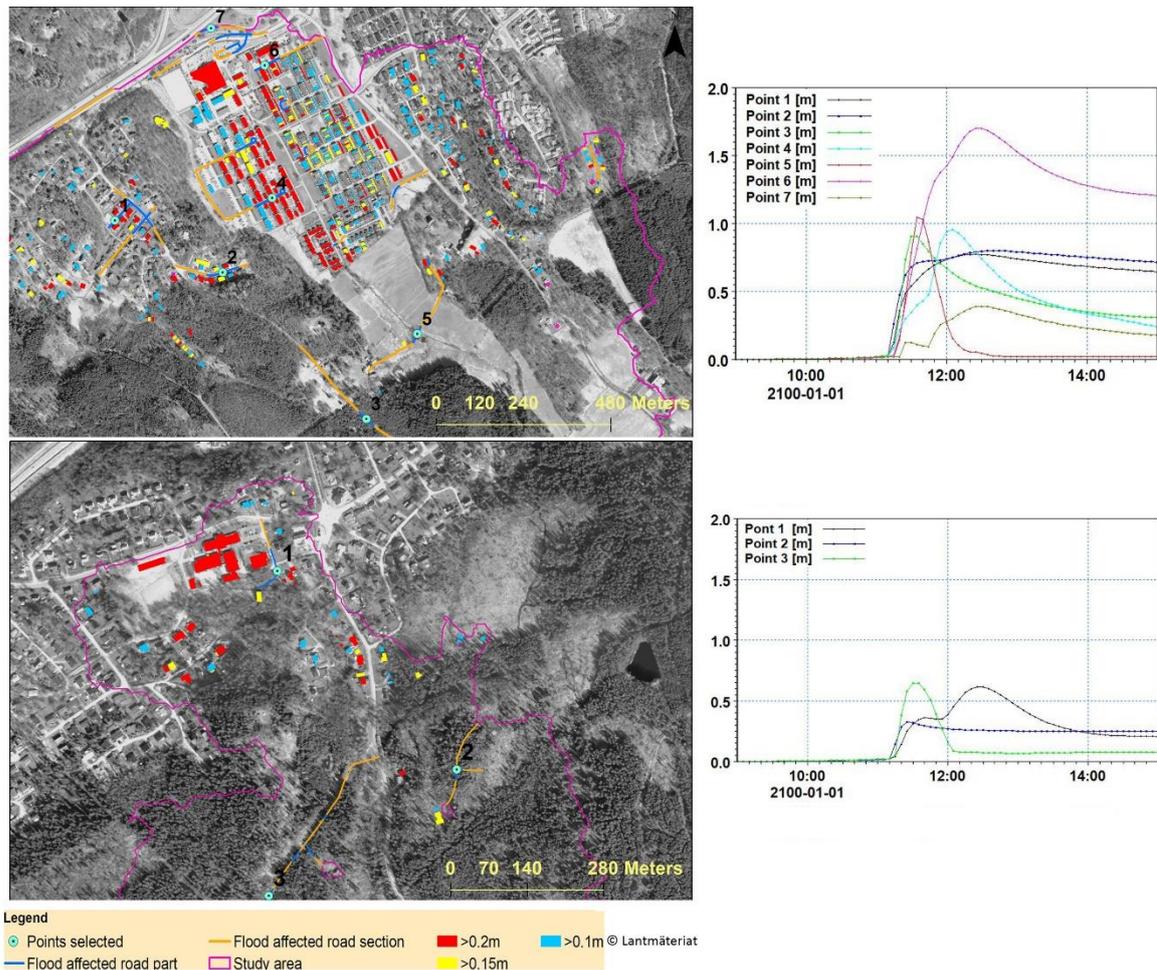


Figure 8 Vulnerable infrastructure during a 100-year rainfall event and temporal variation of flood depth at the selected road points for the two study areas: Hulan (top) and Berghultskolan (bottom)

4.1.2. Public spaces

Figure 9 is a flood risk map that shows vulnerable zones within the study areas that contain risk to human life during the 100-year rainfall event. The map was developed based on guidelines from MSB (2014) as mentioned in section 3.5. The figure shows higher risk for public in Hulan than in Berghultskolan. Moreover, in Hulan study area, extreme vulnerable zone is apparent specifically at two different locations: at the area containing the downstream point and at the area next to open field where a natural meander exists. In Berghultskolan, medium scale vulnerable zone is present at the downstream point, hence creating a hazardous environment for the school children. No other places except the downstream point in the Berghultskolan seem to pose risks to the public.



Figure 9 Flood zones posing risks to human life during the 100-year rainfall event obtained by combining flood depth and flow for the two study areas: Hulan (top) and Berghultskolan (bottom)

4.2. Critical analysis of flood risk

This section shows different flood hotspot zones, spatial extent of flood depth and the flow direction in the two study areas. It also includes a simple illustration on flow direction from different flood hotspot zones and its associated pathway in land surfaces through which it leads to the downstream point.

4.2.1. Hulan study area

Hulan study area was marked into six different flood hotspot zones (see Figure 10). A schematic figure showing the flood direction from different zones is shown in Figure 11 below. The downstream point that lies in zone three received water directly or indirectly from all other flood zones. Volume of water contained in each flood hotspot zones from one to six are 6,500 m³, 12,000 m³, 60,000 m³, 19,000 m³, 41,000 m³, 40,000 m³ respectively. It is apparent that if the downstream point located in flood hotspot zone three is to be protected from the flooding event, flood mitigation measures are necessary in other flood hotspot zones. An exemption was at flood

hotspot zone six which contributed extremely low to the downstream point compared to other zones, so no solution was deemed necessary for this zone.

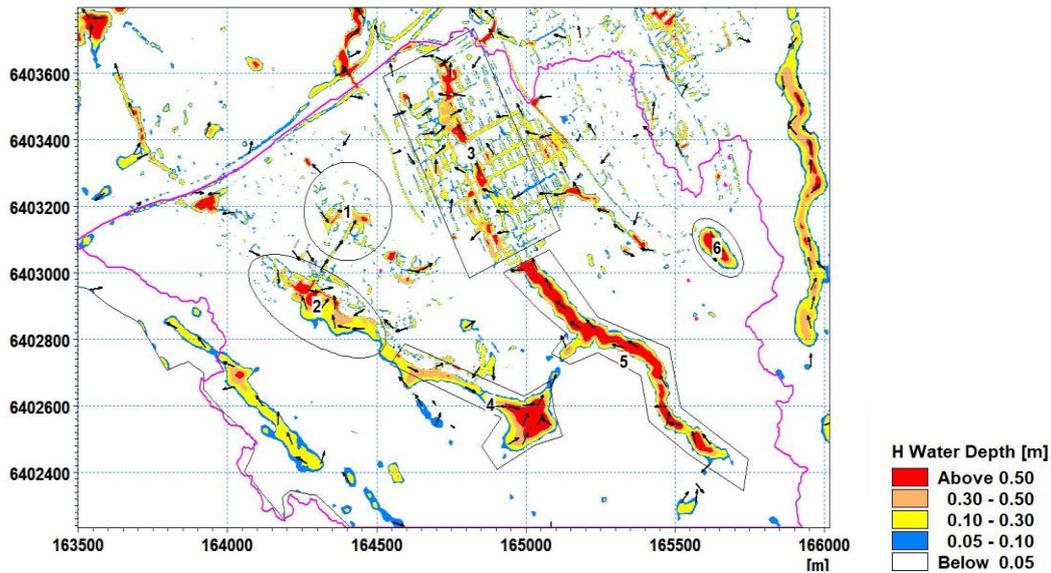


Figure 10 Marking of flood hotspot zones and flow direction in the Hulan study area during the 100-year rainfall event at 11:30 am

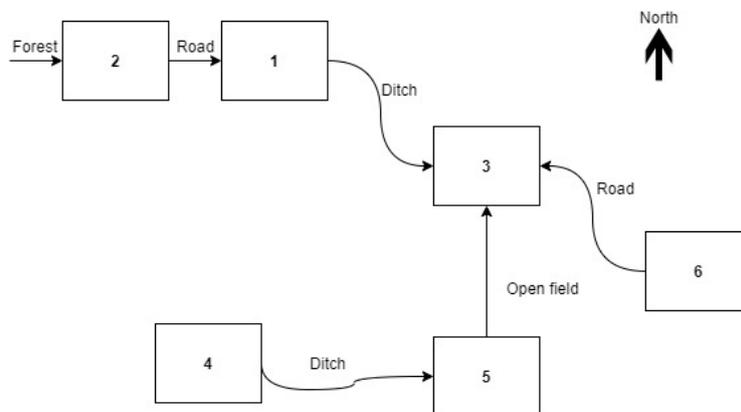


Figure 11 Schematic diagram of flood path in Hulan study area obtained by critically analyzing flow direction from different flood hotspots zones

4.2.2. Berghultskolan study area

A simple model with two flood hotspots zones is shown in Figure 12 for Berghultskolan area where zone one includes the downstream point. A schematic figure showing the flood direction from different zones is shown in Figure 13. Volumetric analysis of the MIKE 21 result showed about 12,000 m³ of water, almost half of zone one, was in fact overflowing from zone two to one. It was concluded that if the flood from zone two can be contained within itself, it would significantly reduce the effect on the downstream point.

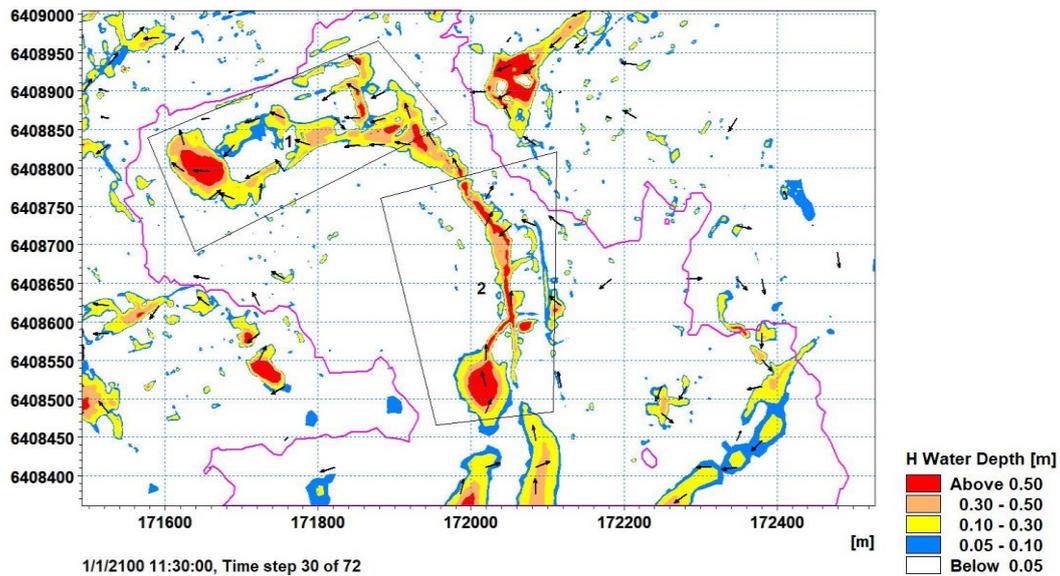


Figure 12 Marking of flood hotspot zones and flow direction in the Berghultskolan study area during the 100-year rainfall event at 11:30 am

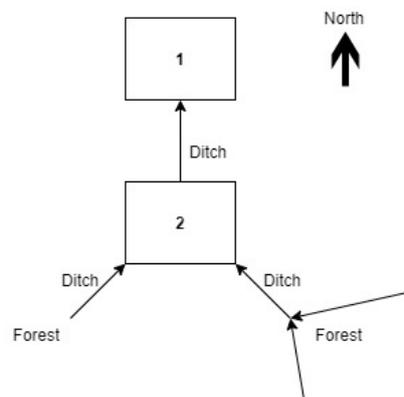


Figure 13 Schematic diagram of flood path in Berghultskolan study area obtained by critically analyzing flow direction from different flood hotspots zones

4.3. Proposed blue-green solutions

This section first lists the proposed blue-green solutions in each flood hotspots zones for the two study areas and the motivation for selecting them. Solutions are proposed after consultation with the municipality followed by their feasibility study performed during the field visit. This is accompanied by showcase of locations where these solutions are proposed. This section further includes explanation to design consideration taken and references followed while designing proposed solutions. Finally, this section shows the cross-sectional view of the proposed blue-green solutions in the two study areas.

4.3.1. Hulan study area

Location of proposed blue-green solutions for Hulan study area is shown in Figure 14.

Zone one: This zone contained mostly residential houses where the excess water during the extreme event reached towards road junction and to its surrounding houses. A drainage canal was proposed for the area to divert the water from zone one into an open space through the channel which starts from the road round one of the houses and through the forest down the hill. Length of the channel is so designed that the longitudinal slope does not exceed 5% (CIRIA, 2017).

Zone two: It was observed that the zone was under construction and new residential houses were built. There existed a stormwater pond in the area that collected water from the surrounding forest. Increasing the size of the pond would collect more water and prevent it from reaching the road. A multilevel stormwater pond was proposed for the area with three different pond levels where the deeper depth lies far from the residential house. Difference in elevation in each level is 0.5 m.

Zone three: It was the most critical area since it contained mostly residential houses. Moreover, as the zone contained the lowest point in the catchment, it was not technically possible to divert water from this zone. It was decided to use small pockets in the area and use it as detention basin to store water. Altogether four places were found, see Figure 14. The first two collection units would collect runoff from zone one in two different steps. The latter two detention ponds are in the middle of the residential zone. These spaces were proposed to be used as multifunctional area that provided recreational space as well as collect stormwater during an extreme rain event. Existing drinking water pipeline system were marked to avoid excavation in that area.

Zone four: This zone mostly contained open spaces. A creek was spotted that diverted water from the area into zone five. It was decided to shut the creek and collect water in the open space and use it as a wetland. To further increase the volume of stored water in the wetland, it was proposed to increase the road elevation by 1.5 m.

Zone five: Highest volume of flooded water into the downstream point entered through this zone. The area possesses steady decline in slope from the open space into the residential area. This increases the concern for municipality since the area possessed flooding risk from both flow velocity and water depth. Moreover, the area includes a natural meander that has very low bend. Therefore, a new meander was proposed with larger bend to use the bends to decrease the velocity. Furthermore, the cross section of the meander was decided to be used as 2-stage channel according to the recommendation from Vättra Götaland Län. The bottom section of the channel would transport the sediment while the top section regulated flow.

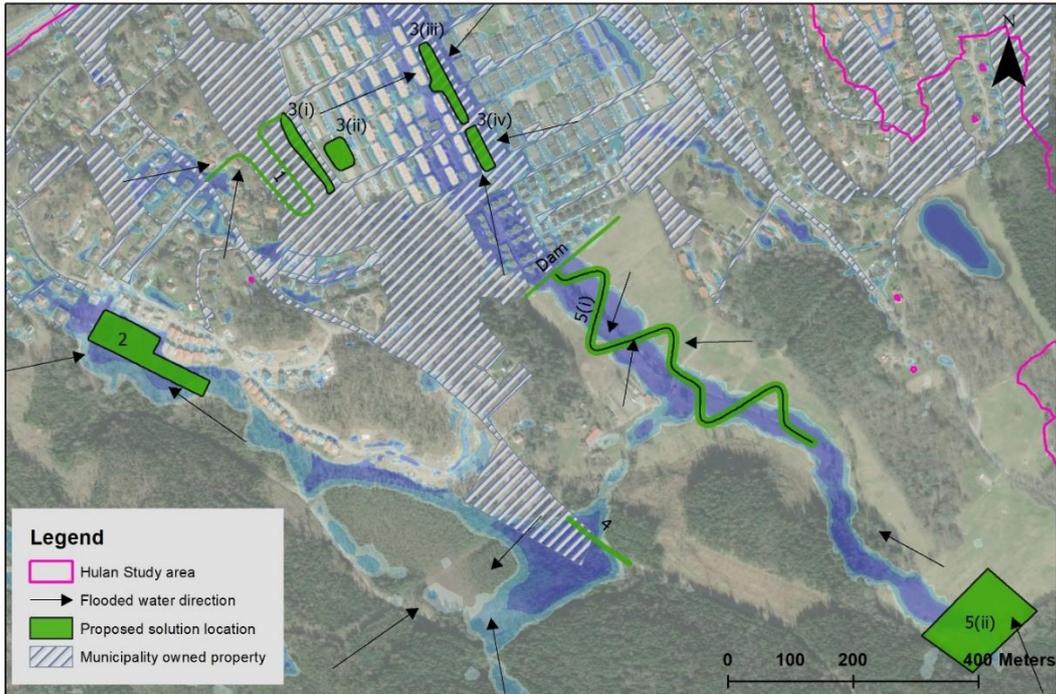


Figure 14 Aerial view for location of proposed blue-green measures for the Hulan study area

Figure 15 shows cross-sectional view for each solution. The figure shows cross-section corresponding to the width section for all solutions except multilevel stormwater pond. In case of multilevel stormwater pond, the cross-section view is drawn for longitudinal axis to show length of each pond and height difference among ponds.

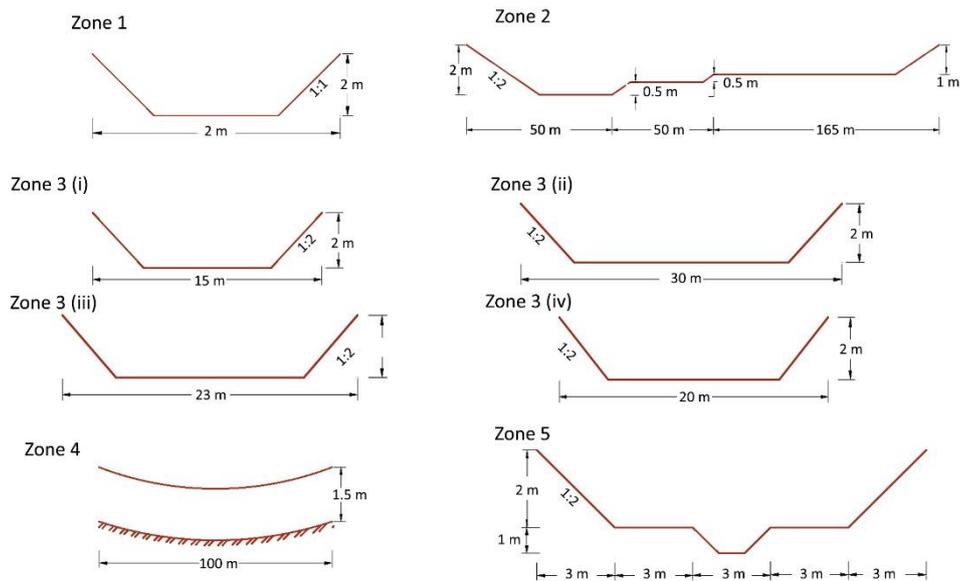


Figure 15 Cross-sectional view of proposed solution in Hulan study area

4.3.2. Berghultskolan study area

Location for proposed blue-green solution for Berghultskolan study area is shown in Figure 16.

Zone one: Lowest point of the study area that lies next to the school Berghultskolan. Like Hulan study area, downstream point in Berghultskolan study area facilitates no provision to divert water into a water bodies like lake or river and thus we looked at possible alternatives where the flooded water could be collected safely. Adjacent to school buildings is a parking lot, school playground and an open space. These spots were recommended to be utilized as a multilevel stormwater detention pond by the municipality similar to the one proposed in zone two in the Hulan study area. First, the open space towards the eastern part of would be utilized followed by playground and then the parking lot and finally to school corridor before the water enters the school buildings. This solution would aim to transfer the flood risk from the school area as far as possible. The next objective was to identify a safer route to divert water into this multilevel stormwater detention basin. Bicycle track next to the school was identified as a possible route. Drainage channel in either side of the bicycle was proposed to divert the water into the detention basin. Channel one diverted water from downstream while channel two diverted water collected within the eastern part of school premises.

Zone two: Potential stormwater collection spots that could be utilized to store water were assessed in zone two. The main objective of this solution was to collect the water from the upstream forest area and prevent it from reaching downstream. An open space next to the road was adjudged appropriate to be utilized as a stormwater detention pond. Next to this unit is an open space which was proposed to be utilized as a wetland when the capacity of stormwater pond is exceeded. Terrain adjustment was deemed necessary in the downstream point of the pond to maximize the usage of wetland.

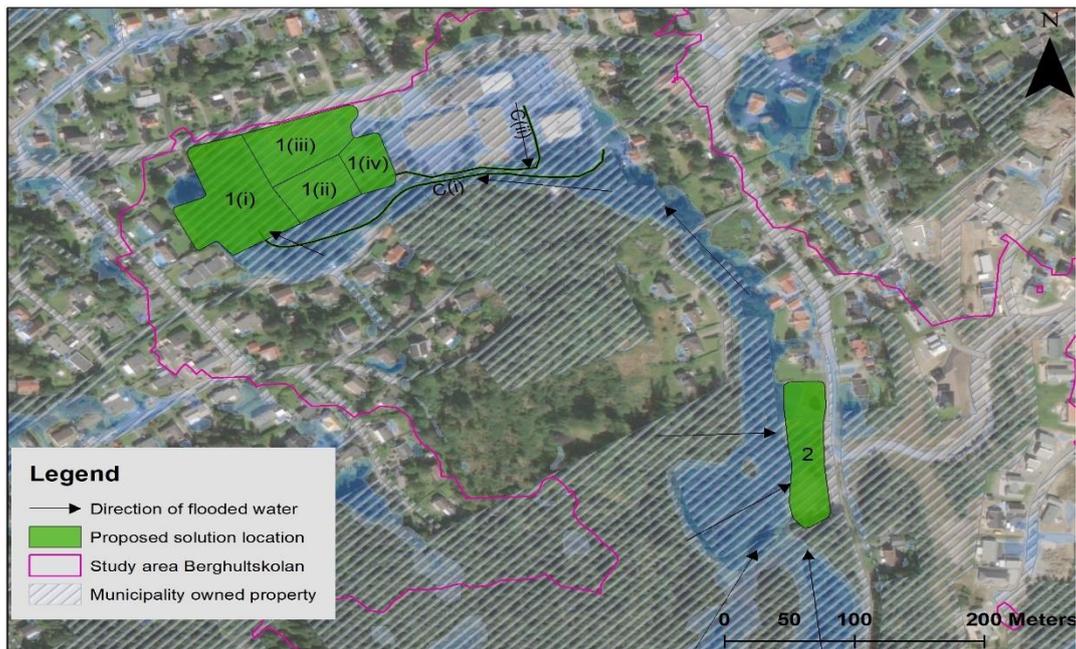


Figure 16 Aerial view for location of proposed blue-green measures for the Berghultskolan study area

Figure 17 shows cross-sectional view for each solution. The figure shows cross-section corresponding to the width section for all solutions except multilevel stormwater pond. In case of multilevel stormwater pond, the cross-section view is drawn for longitudinal axis and dimension of length for each level is shown in Table A4, Appendix A.

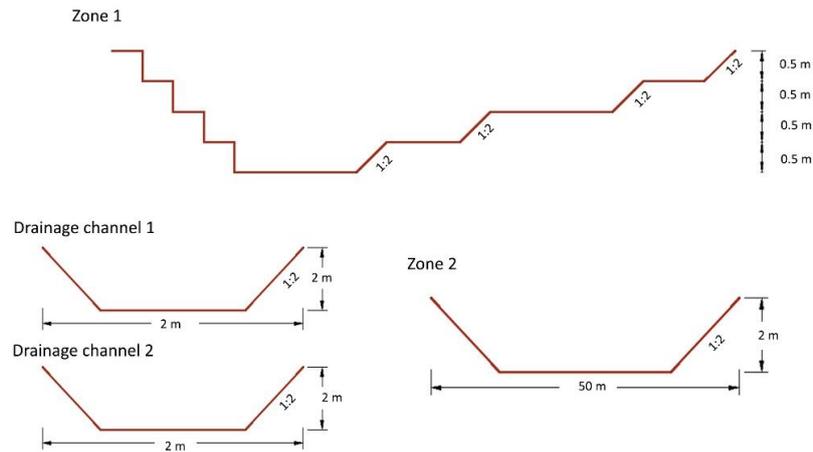


Figure 17 Cross-sectional view of proposed solutions in Berghultskolan study area

4.4. Effect of blue-green solutions

Proposed blue-green solutions for the two study areas were defined in two computer models SCALGO Live and MIKE21 with reference to the cross-sectional design shown in section 4.3. Effectiveness of the solutions was tested for 100-year rainfall event using both models.

4.4.1. Preassessment with SCALGO Live

Figure 18 below shows the extent of flood before and after implementing the blue-green solutions for both study areas.

In Hulan study area, except two detention ponds (3iii and 3iv) which failed, all solutions effectively controlled the flooded water before reaching their maximum capacity. Canal (in zone one) successfully diverted the excessive water from the flood zone into the flood designated space. Multilevel detention ponds (zone two) were found efficient to collect the flooded water in a secured environment. In zone three, first two detention ponds (3i and 3ii) effectively contained the urban runoff from zone one. In zone four, a wetland was formed as expected where the water was distributed. Finally, in zone five, the flood meandering was found effective in both collecting and diverting flooded water. Similarly, stormwater pond at the upstream point was utilized effectively to contain the excess runoff water upstream. However, despite implementing different mitigation measures both upstream and downstream, the flood risk at the downstream point was still very high.

In Berghultskolan study area, the proposed solutions were found efficient against the 100-year rainfall event. The multi-level stormwater detention pond effectively contained the flooded water. In fact, only three levels out of maximum four of the detention ponds were utilized and the maximum depth was 1.27 m at level one which is about 0.7 m below its maximum design capacity. Similarly, both channels efficiently diverted the flooded water into the multi-level detention pond before almost reaching their maximum designed capacity during the flood diversion process. Detention pond in flood zone two was also close to its maximum design capacity.

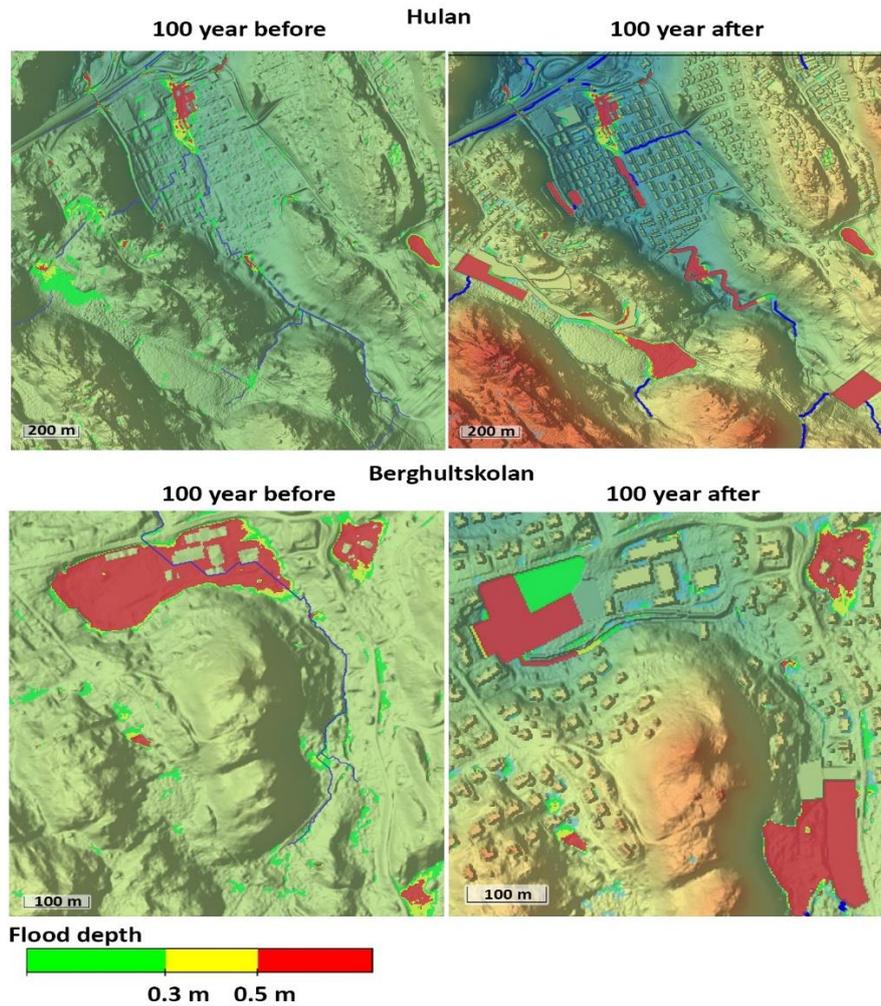


Figure 18 SCALGO Live output on the extent of flood depth during 100-year rainfall event obtained before and after implementing blue-green solutions in the two study areas Hulan (top) and Berghultskolan (bottom)

Sensitivity of the proposed solutions was tested for rainfall events with 400-year and 1000-year return periods. Figure 19 below shows the extent of flood during 400-year and 1000-year rainfall events for the two study areas. The effectiveness of the proposed blue-green solutions in Hulan study area was found poorer compared to the Berghultskolan study area.

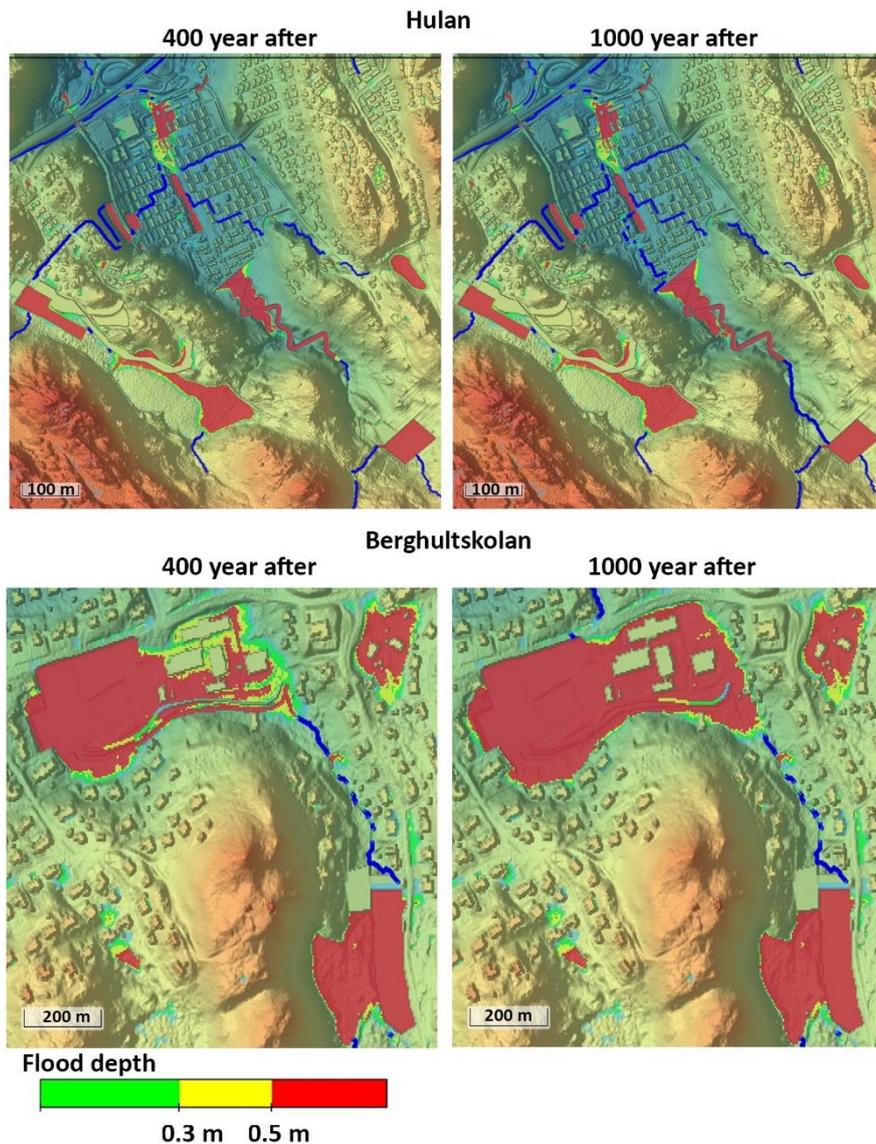


Figure 19 SCALGO Live output on the extent of flood depth during 400-year and 1000-year rainfall event obtained after implementing blue-green solutions in the two study areas Hulan (top) and Berghultskolan (bottom)

In Hulan, during 400-year rainfall event, solutions in the first three zones exceeded their design capacity. Meandering on the other hand was still functional and the barrier wall was not yet breached. Similarly, raised road elevation in zone four was still in effect to contain the water in the wetland. Water level in the downstream point exceeded 1.5 m. During the 1000-year rainfall event, situation worsened further, as expected. Every solution except zone four have reached their design capacity. The wall in the meandering upstream could no longer resist the flooding water.

In Berghultskolan, during 400-year rainfall event, stormwater pond downstream exceeded its capacity and hence more water entered the detention system. Both drainage canals were flooded in multiple locations after reaching their capacity. All four systems were filled with water and as a result water entered the school building premises. Maximum depth in the school area was over 0.5 m in the western school area. A more extreme rainfall further increases flood extent as expected as shown in the Figure 19 above. The area is inundated 1.5 m during the 1000-year rainfall event.

4.4.2. Effectiveness of proposed solutions in MIKE 21

Details on the MIKE21 model setup to model the performance of the proposed solutions are explained in section 3.8. In total, six simulations were performed for three extreme rainfall scenarios and two study areas. Figure 20 below shows the spatial extent of flood depth for the two study areas. Flood direction is not shown since it resembles to that shown in Figure 10 for Hulan study area and Figure 12 for Berghultskolan study area.

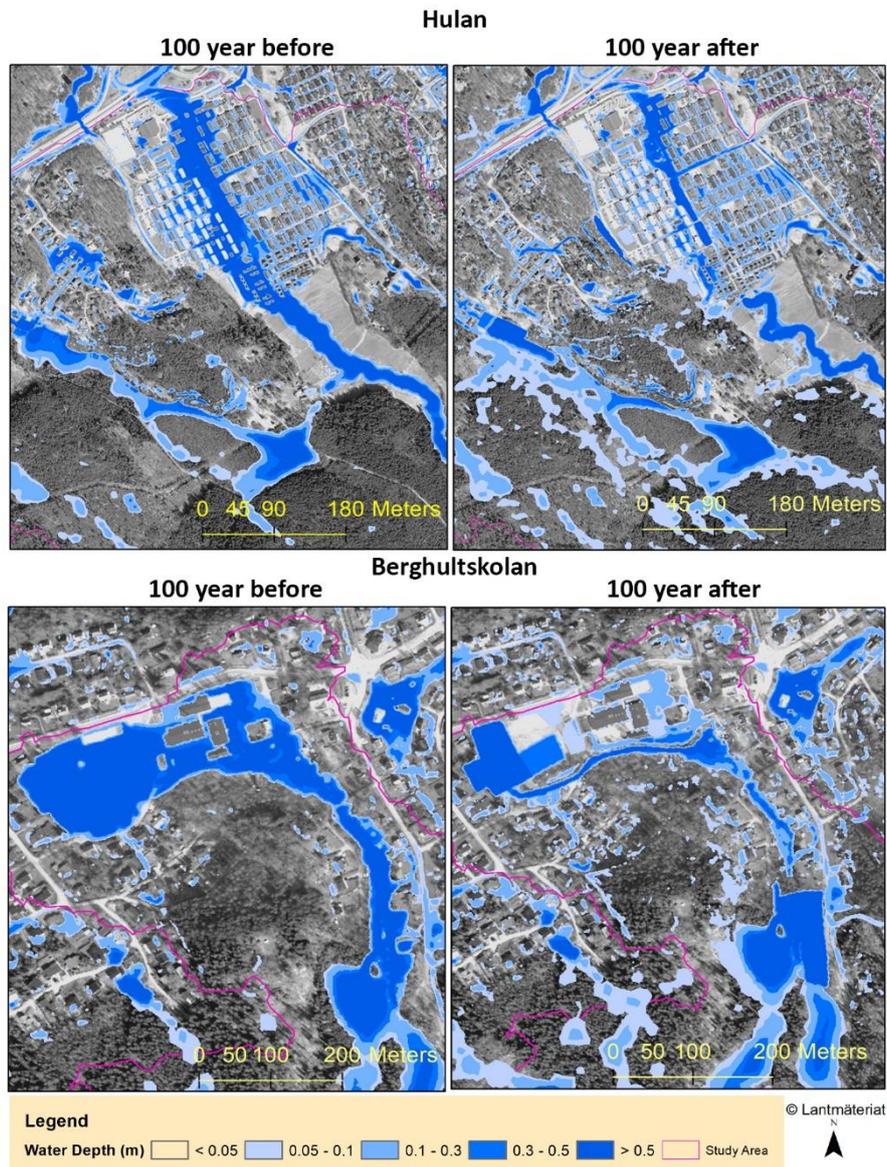


Figure 20 MIKE 21 output on the extent of flood depth during 100-year rainfall event obtained after implementing blue-green solutions in the two study areas Hulan (top) and Berghultskolan (bottom)

In Hulan study area, all solutions contributed significantly to collect or divert the flooding water as expected. Results show that detention ponds in zone three (iii and iv) reached their maximum capacity to further transport excess water into downstream point. The first two detention ponds in the same zone were still functioning even at the end of the simulation period. Maximum design capacity for each solution is shown in Table A4, Appendix A. Figure 20 shows that solutions in zone two and zone four were

also successful in containing water in the designated space. Stormwater pond in zone five was effective in containing the water from upstream forest area, and its design capacity was not reached. Meandering worked harmoniously in collaboration with the raised wall and edited terrain to create a detention pond in the existing meander.

Similarly, in case of Berghultskolan study area, the multi-level stormwater detention pond was found very effective in regulating the flooded water. Maximum water depth of 0.87 m was obtained in the first level, which meant the corresponding depth in the second level was 0.38 m, while the parking lot (level 3) was unutilized to collect the flooded water. Level 4 was primarily utilized to divert water from school building premises to level 2. Similarly, stormwater pond located downstream was efficient and it was still functioning at the end of the simulation period reaching its maximum level. The two canals on either side of the cycle path were close to their design capacity. Maximum depth in the western school area was 0.12 m during the peak rainfall period.

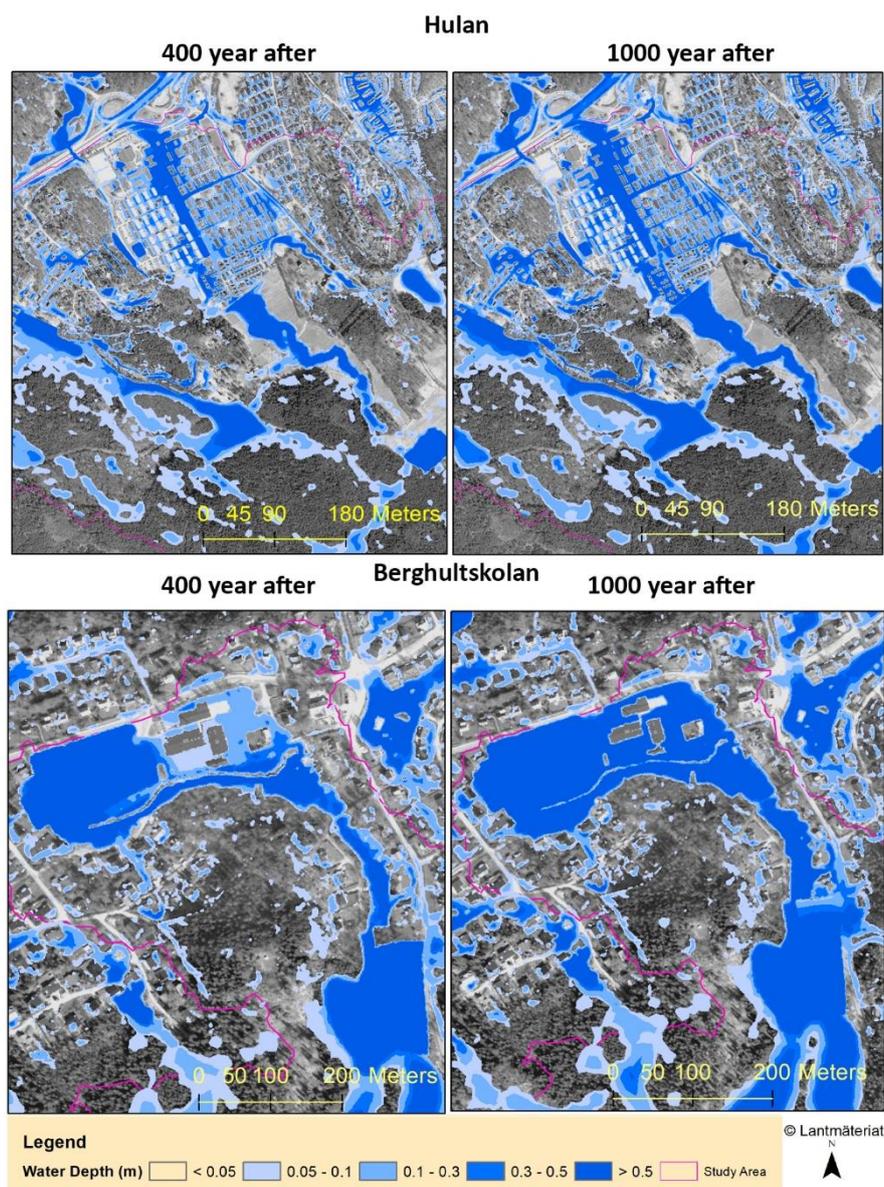


Figure 21 MIKE 21 output on the extent of flood depth during 400-year and 1000-year rainfall event obtained after implementing blue-green solutions in the two study areas Hulan (top) and Berghultskolan (bottom)

Test of solutions during more severe rainfall conditions (400- and 1000-year rainfall event) in both study areas showed larger flood extent than 100-year rainfall event, as expected (see Figure 21). In Hulan study area, all solutions exceeded their design capacity during the 400-year rainfall event. As a result, deeper water level was seen at the downstream point up to a maximum value of 1.4 m. Flood extent further increases during the 1000-year rainfall event affecting most houses and streets in the area. In Berhultskolan study area, the extremely effective multilevel detention system for 100-year rainfall event was overwhelmed by the 400-year rainfall event. However, the maximum water depth in school area was only 0.12 m for only a short duration of ten minutes. Technically, school building area was still safe from the flooding risk. In case of 1000-year rainfall event, however, the situation worsened beyond living condition, and the entire depression area was at risk of over 1.5 m flood depth.

5. Discussion

5.1. Vulnerability assessment

The aim of performing vulnerability assessment was to increase awareness and knowledge of threats and risks of flood, and to obtain a basis for planning for the municipality. Risk and vulnerability analysis help to reduce the vulnerability of society and increases the ability to manage crises and extraordinary events. Indeed, results show that almost half of the total number of buildings in both Hulan (44%) and Berghultskolan (49%) study areas are vulnerable to urban flooding risk during the 100-year rainfall event. Further on, more than 20% of the total houses in both areas is susceptible to flood depth higher than 0.2 m, which indicates that residents in these areas live in a high-risk zone. Although the flooded water dissipated throughout the area affecting most residential zones, the most critical effect was seen at the downstream point in the Hulan study area where the flood depth was greater than 0.3 m for some houses. In Berghultskolan study area, the school itself was observed highly vulnerable with children being exposed to this hazardous environment.

Similarly, roads in both study areas were also observed to be under flooding risk. However, the severity was significantly higher in Hulan study area than in Berghultskolan study area. Flood depth in the selected points (1, 2 and 6) passed the critical limit of 0.3 m water depth. In fact, water depth remained above critical limit even towards the end of the simulation indicating that the water will continue to remain in the system for longer time. This would invite a severe risk to the traffic system by jamming the transportation network for longer periods. Emergency services including ambulance, police and fire trucks would become unavailable for public support. Thus, during such highly hazardous situation when public demand for emergency services is very high, unavailability of these services could trigger panic in public. Additionally, the biggest concern for the municipality would be the effect of the flood on the major highway. Governmental authorities usually implement evacuation process during hazardous events. Misfunctioning of a major highway during such emergency condition would create catastrophic impact impeding the transportation network. In Berghultskolan study area however, significantly less impact was observed on road network. Most affected roads are local streets containing the possibility for alternative route to lower the flood impact risk.

Vulnerable open space to public was assessed to study an integrated effect of both flood depth and velocity. As expected, zones with higher vulnerability scores were obtained in Hulan study area due to the higher magnitude of the flood in the area. It should be noted that the vulnerable open areas lie in the vicinity of maximum human settlement. Figure 9 shows that people from all age groups live in the flood risk zone. Areas marked by high risk value but located upstream should be of relatively less concern for the municipality, since these are open space mainly used for grazing cattle. However, this region includes open flow channel containing natural bend, thus, higher flood depth and velocity could trigger a landslide. In Berghultskolan study area, the result shows the playing field is hazardous for school children. Concerned authorities thus have an important task to solve the problem. In upstream, only the existing creek posed slight risk to humans which could be easily avoided by taking necessary precaution.

Thus, the results show that both study areas were highly vulnerable from infrastructure and public health risk perspective. Most critical areas were located downstream; this further exacerbates the magnitude of the problem since water cannot be transported

elsewhere. Moreover, it is not economically feasible to divert water from the downstream point to another location. These circumstances gravitate towards the need for onsite flood risk mitigation measures. The method adopted using blue-green measures serves as the right solution in this case to reduce the flood damage.

5.2. Uncertainty in vulnerability assessment

Model calibration, sensitivity and uncertainty analysis are all vital issues in determining the accuracy and strength of model results (Fletcher et al., 2007). No calibration of the model output was performed during the study due to limited time constraint of the thesis work. Similarly, no data was obtained from the municipality or the consulting company Tyréns on the calibration of the model. However, calibration of runoff processes in torrential rain is seldom possible, because there are often no measurements of rainfall and observations of flood extent and depth of water (MSB, 2017). Additionally, extreme rainfall is often very local, and rain intensity can vary a lot in both time and space.

One major limitation in the study was assumption of stormwater network capacity equivalent to 2-year rainfall event. Although MSB suggests it is reasonable to assume stormwater drainage capacity for pipelines to 2-year rainfall event, its consequences cannot be avoided. This assumption could highly lead to uncertainty in flow volume in the area and hence the damage induced. In both the study areas, high percentage of land is covered by forest where no pipeline exists, deduction of 2-year rainfall would lead to significant underestimation of flow amount. Similarly, in case of residential areas, pipeline drainage capacity highly varies depending upon density of houses in the area. For instance, Lerum has a combine sewer system, common to stormwater and wastewater. Higher population density means more amount of wastewater flow in the pipeline and thus less capacity to drain the stormwater. In such case, assumption of pipeline drainage for two-year rainfall event would be overestimation of reality. Similarly, in lower population density area, pipeline drainage capacity would be higher due to less volume of wastewater flow. This will result in underestimation of reality for stormwater network capacity. The uncertainty arising due to assumption of stormwater network capacity could have been avoided by introducing a coupled model which combines 2-dimensional surface flow from MIKE 21 and 1-dimensional flow in pipeline from MIKE 11. However, due to shortage of technical knowledge for the program MIKE 11 and due to limited time constraints of the thesis work to impede learning the tool, it was not considered.

On a different note, when the output data from MIKE 21 were imported into ArcGIS, a slight loss in data magnitude was noted. MIKE 21 gives output in a dfsu file type, where data is stored in a flexible mesh data structure. To import this data from MIKE 21 to ArcGIS, the dfsu format is first converted into a grid series file (dfs2) and then to ArcGIS friendly raster file with extension (.asc). Further, to extract specific values from the asc file, for example spatial extent of flood depth greater than 0.1 m, different spatial analysis is performed in the raster file in ArcGIS. Further conversion from raster to vector file was required since land use data file was obtained in a vector format. Finally, buildings or roads that intersect the converted vector file was selected as the flood vulnerable infrastructure. Moreover, the model output passes through series of intricate process involving conversion of data file and different GIS operations. As a

result, slight loss of data was noticed. In this case, the result of the test will give underestimation of reality.

Furthermore, the model has not analyzed flood mitigation measures adapted by the locals including elevated roads, fences, permeable and infiltration trenches that could substantially mitigate flood effects. The modelling outcome would in this case be an overestimation of the reality. Similarly, in places where there is normally a water surface (such as rivers and ponds) the vulnerability score underestimated, since the height of the model used in the downpour mapping does not show the bottom topography without water (Defra & Environment Agency, 2006).

Another factor that would lead to uncertainty in the accuracy of vulnerability assessment is due to lack of synchronization between land use map and the mesh file. As can be seen in Figure 22, buildings boundary marked by black line does not always coincide with buildings in the mesh. As a result, during simulation water will flow in the foot of the building of the mesh since it is lower or equivalent to neighboring cells. Since the boundary of the building in the land use map however extends outside the building elevation, GIS will interpret this as a part of the house and hence, regard it as the flood vulnerable building as shown by (Larsson, 2012). This discrepancy in synchronization between the land use map and the mesh file occurs due to error while creating mesh file or due to lack of sufficient data points. More data points will generate finer and more accurate mesh while less control points generate a less accurate one.

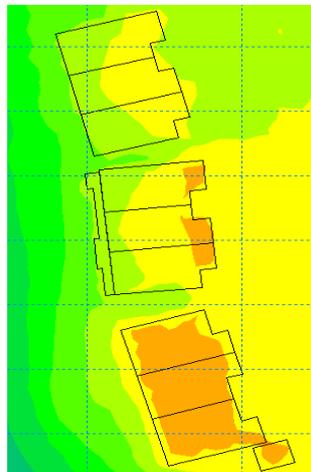


Figure 22 An example of computational mesh and land use map not synchronizing. Building extent in land use map is shown by black line marker while bottom layer is a part of flexible mesh used in MIKE 21

Similarly, within the elevation mesh, buildings structures appear more as rounded hills. If the mesh had been a true reflection of reality, the houses would then have been blocks in the mesh and surface water would then flow across the model area, see Figure 23. Thus, if the mesh and land use layer had perfectly synchronized in this case, no flood depths would ever be interpreted as a flooded building since the flood maps would never have cut in over the buildings in the land use maps as long as the entire building is not under water. In this case the results of the test will be an underestimation of the reality. This shows that site visits to each facility are required to ensure that the actual altitude conditions are consistent with those that formed the basis for the modeling.

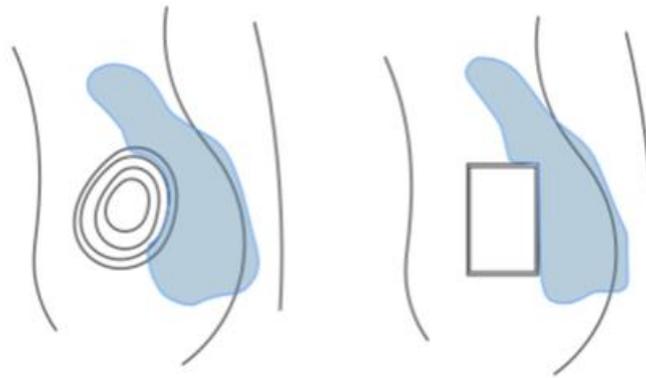


Figure 23 Schematic diagram of surface water spread in mesh for two different elevation condition. In this case, left model would be interpreted as flooded while right model would not. Image source: (Larsson, 2012)

Further uncertainty in vulnerability assessment could be added by local geological conditions. Soil type and water content is highly related to soil stability (Herrmann & Bucksch, 2014). For example, if the soil layer in the area is below the marine limit (the highest position reached by the postglacial sea at a site) like neighboring Gothenburg city, there is possibility of high soil settlement during the rainfall event. Soil layer below marine limit are characterized by marine deposits that consist of high salt content. When this soil contacts water, salt dissolves and flows along with water creating void in soil stratigraphy, hence resulting in high soil settlement risk. This can increase the amount of vulnerable infrastructure. Furthermore, study area Hulan includes steep slopes and hence could be vulnerable to landslide. Presence of clay from marine deposits would further increase the risk of landslide thereby affecting more infrastructure in the area. In our study, we have only considered the effect of velocity and volume of flooded water, but not flow of debris or risk for landslides. Therefore, further detailed flood vulnerability assessment could be performed emphasizing the study of debris flow and the landslide risk as advised by Eximap (2007).

5.3. Proposed solutions effectiveness

High flood impact was observed in the downstream point in both study areas; suitable blue-green measures were hence implemented in the upstream areas, marked by flood hotspots zones, to reduce the flow into the downstream points.

In Hulan study area, all proposed blue-green measures except the ones in zone three (iii) and (iv) were observed effective to control the flooded water during the 100-year rainfall event. In zone three, there was not enough space available to accommodate the flooded water and hence, the downstream point was still under high flooding risk. Although significant changes were observed with over 0.5 m of flood depth reduction, the area is still very critical. A possible reason for this is since this is a downstream point, water cannot flow away from this point and it will only accumulate over time. As soon as the capacity of the proposed solution is reached, all the excess water takes a new route and accumulates at the downstream point. In flood zone two, the proposed solution was capable of handling a 100-year rainfall event, but during a more extreme rainfall the solution's capacity was surpassed, as expected. As a result, the excess water reached the solution in zone three (i) flowing through the street and the canal of zone one. This accumulated water overwhelmed the solutions capacity in zone three (i) and

(ii). Consequently, the excess water further continued to the downstream point creating a so called 'flow coincidence effect' there. This flow coincidence effect would create a synergetic effect in the downstream point to further increase the flood risk there. Hence, this flow coincidence effect should be noticed during the decision-making process while designing blue-green measures for the area. Also, it was obtained that solution in zone four was efficient in controlling flood during all extreme rainfall events. However, it was observed that the flooded water could not dissipate uniformly due to difference in the elevation. It should be further noted that wetlands have very limited capacity to reduce overall runoff volume, since their only loss are due to evapotranspiration (Fletcher et al., 2007). In zone five, combination of meandering and two stage channels efficiently regulated the flooded water. Moreover, meandering bends were also effective in reducing the flow velocity. It should be noted that the mesh size was in excess of 10 m, which restricted the possibilities to adjust the geometry of the solution as desired. As a result, with a coarser resolution the flow distributed in larger areas as designed resulting in less water depth to create a so-called 'flow smearing effect' as pointed out by Adullah et al. (2012) and Vojinovic et al. (2011).

Due to abundance of open space upstream in the Berghultskolan study area, a big proportion of flowing water was securely contained in the upstream pond. Moreover, the detention pond system at downstream also was large enough to control the remaining flood water flowing during the 100-year rainfall event. Overall the stepwise solution proposed for the Berghultskolan study area was found suitable for 100-year rainfall event. For more extreme rainfall, the solution still functions for the 400-year rainfall event, while it reached its capacity during the 1000-year rainfall event. The result shows a risk-free downstream point, but still necessary precaution should be taken to avoid any undesired health risk to school kids.

Effect of the proposed blue-green solution can be evaluated through Figure 24 which shows temporal distribution of flood depth at the selected point for the two study areas. In Hulan, the downstream point itself is the reference point, since it includes high number of residential houses. Similarly, for Berghultskolan, adjacent open space next to the school buildings was selected, since this point gives the best representation of flood depth at the school buildings. As clearly seen in Figure 24, the school buildings are safer during the 100- and 400-year rainfall events. These data give further illustration on the effectiveness of adopted blue-green measures for the study area. Additionally, it can be further interpreted that the proposed solution is still functioning towards the end of the simulation since the water depth at the critical point is still marginal. However, the school is heavily affected by flood during the 1000-year rainfall event irrespective of implementation of solutions. In case of Hulan study area, as mentioned earlier, the downstream point is still very critical. However, it is observed that over 0.5 m of flood depth is reduced during the peak hour. The assumption of the study that the stormwater network is equivalent to 2-year return period cannot be neglected in this case. If the drainage network at the area is larger than the 2-year capacity, then the water depth seen in the graph would reduce significantly. In such case, the risk from flooding would be significantly less than what is shown in this study.

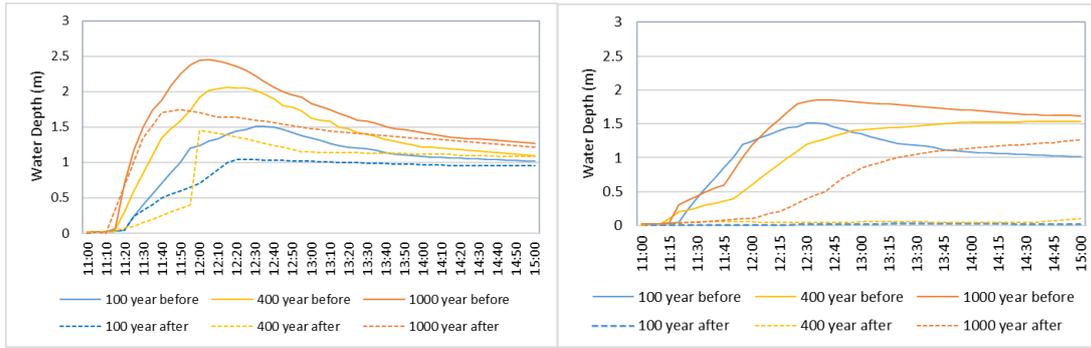


Figure 24 Flood depth at selected critical points for 6 hour simulation period for Hulan (left) and Berghultskolan (right) during 100-, 400- and 1000-year rainfall event

Proposed blue-green measures effectiveness is analyzed by comparing the effect on infrastructure before and after their implementation. Before interpreting the bar diagram in Figure 25, the uncertainty associated with this analysis, which is described in section 5.2 should be referred. Figure 25 shows that the number of buildings affected by higher flood depth is reduced more significantly than the number of buildings affected by the lower flood depth. Roads have greater reduction in impact compared to buildings. It is because roads are compared to single point value of 0.3 m, while buildings are compared to three different values. In case of road, 0.3 m is the highest limit, and given any slight reduction below this level Arc GIS will not include this as the affected road. While in case of buildings, slight reduction from the highest point of 0.3 m is still included in the lower categories of 0.2 m and 0.1 m respectively.

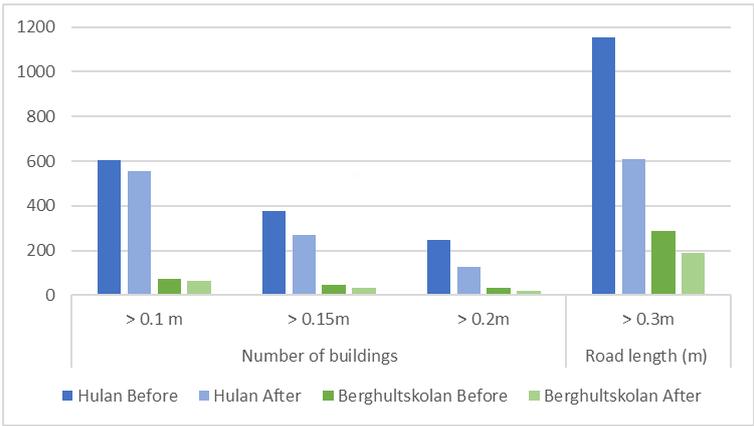


Figure 25 Number of buildings and length of road affected before and after implementing blue-green measures in two study areas during the 100-year rainfall event.

Overall, this study shows proposed blue-green measures are very effective in controlling urban runoff volume if adequate space is available. This study agrees with Wihlborg et al. (2019) who claims properly planned blue-green measures effectively regulate flooded water in urban system and thus are instrumental to protect human life and property in a changing climate. Further supported by Eckart et al. (2017) who claims integration of different blue-green measures, like detention ponds will often be the best alternative to accomplish stormwater control objective as well as achieve key elements of natural flow regime. However, lack of proper planning could lead to

deteriorative flow coincidences as pointed out by Haghghatafshar et al. (2018a). For instance, in a complex urban system of catchment-sewer interactions, even detained discharges from catchments can possibly coincide with some peak discharge along the way causing elevated hydraulic head and, hence, flooding. This effect was precisely witnessed in our study where excess water from zone two in Hulan area caused water level to increase in zone three (i) during 400- and 1000-year rainfall event. Haghghatafshar et al. (2018b) in another study while accessing effectiveness of blue-green measures in urban space, recommends using blue-green measures in the upstream area of a city catchment to avoid or decrease the risk of flow coincidences.

5.4. Comparison of SCALGO Live and MIKE 21

Results from the two-computer models MIKE 21 and SCALGO Live were very similar despite that these models use different mechanisms to simulate stormwater runoff. Indeed, all canals in the two study areas transport water very effectively into their desired destination. In terms of solution capacity, both models showed for the 100-year rainfall event that these canals are well below their critical limit. Similarly, multilevel detention ponds in both study areas effectively controlled the 100-year rainfall event in both models. Similarly, meandering and wetland in Hulan study area and stormwater pond in Berghultskolan study area showed similar results in both models. Downstream point in Hulan was shown as critical even after implementation of solutions in both models as mentioned earlier. During the 400-year rainfall event, in terms of capacity, no significant differences between the output from the two models were observed.

However, some differences were noticed between the two models. In Berghultskolan detention pond, for example in level 1, deeper water level was observed in SCALGO Live (1.28 m) than in MIKE 21 (0.87 m) during 100-year rainfall event. As an effect, solution level 2 was fully saturated, and approximately 0.2 m of parking lot was filled in in case of SCALGO Live. In MIKE 21, however, water depth in level 2 was still below its maximum capacity leaving level 3 unutilized. Similarly, in Hulan study area, detention pond 3(i) was filled leading excess water to detention pond 3(ii), while in MIKE 21, water level in the first pond was still below its capacity limit. A major difference was seen during a 400-year rainfall event in Hulan study area. Water level at the school area was below the critical risk limit in MIKE 21 which indicated the solution network was still functional. In SCALGO Live, however the major flood risk to buildings was apparent.

Although similar results were obtained from the two models in terms of capacity, water depth in SCALGO Live was consistently higher than in MIKE 21. The prominent cause for this is due to exclusion of soil infiltration property in SCALGO Live. Soil properties play an important role in controlling urban flood (Jordbruksverket, 2015). However, soil has limited infiltration capacity and exceeding this value will result in overland flow. This is illustrated in Figure 26, showing that similar differences in water depth were obtained at a reference point when flood depths from different rain events were compared. This is due to soil infiltration parameters that were defined in MIKE 21. Figure 26 also shows that result from two models are almost the same if infiltration parameter is excluded. Hence, there is consistency between the elevation model used in both models since they show similar results. However, it should be noted that this is only valid for areas with uniform geological properties where soil infiltration value does not vary spatially. Similar flood depth comparisons were not performed for other areas due to time constraints.

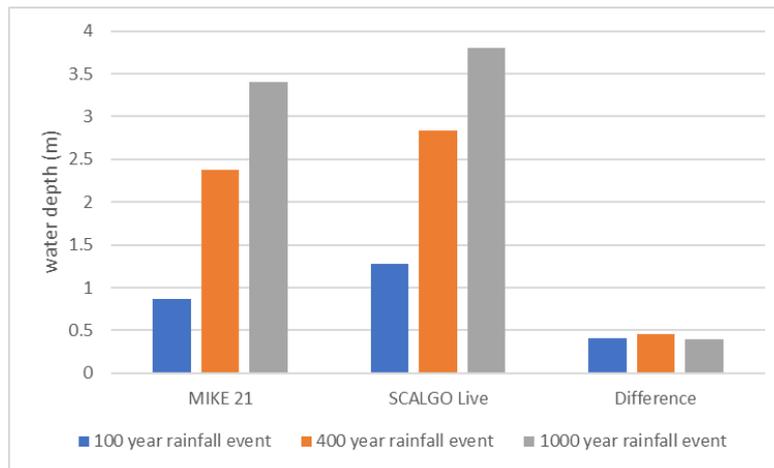


Figure 26 Comparison of Flood depth at a reference point at level 1 of the multilevel stormwater detention pond in MIKE 21 and SCALGO Live

SCALGO Live is a web-based flood simulation tool that uses predefined elevation model to create flood scenarios for selected rainfall event. SCALGO Live does not account for temporal variation and soil properties. It shows end of the line solution and not the process in time. In practice, the maximum water depth occurs at different times in different parts of the model area, which SCALGO Live cannot show. This can lead to underestimation of risk. Further on, although the flow paths can be mapped in SCALGO Live, these cannot be quantified, and thus, their importance is not quantified, which is important during the decision-making process.

In contrast, MIKE 21 simulates the water level and flow in response to a variety of forcing functions using the vertically integrated equations of continuity and conservation of momentum in two horizontal dimensions. It includes soil infiltration properties as well as it accounts for time variations in the study of extent of flood depth. The analysis gives a physically based description of surface runoff and provides a good description of the relationship between the contribution of upstream areas and the volume at downstream point. In terms of output from MIKE 21, the flood hazard map with water depth shows the maximum water depth at the given point at any duration during the simulation period. This is the reason why the flood is more widely spread in MIKE 21 than in SCALGO Live. On the other hand, MIKE 21 does not account for the sewer network capacity. Moreover, MIKE 21 requires good computers with dedicated graphic memories to perform simulations. Finer mesh size and larger domain area consume a large share of computer memory. Similarly, MIKE 21, unlike SCALGO Live, has limited terrain editing tools and thereby requires more manual effort. In MIKE 21, proposed solutions could not be defined in a straight line, since the mesh was triangular and larger resolution in various location of the mesh restricted finer edits in the terrain. Additionally, while editing elevation in MIKE 21, it is important to maintain a backup of the mesh, as suggested by Tyréns (2019) since there is no undo function to revert changes. Another major difference between the two models would be the representation of rainfall data. In MIKE 21, CDS (Chicago Design Storm) model is used, in which time series of maps are created where all grid points are assigned their own values. In SCALGO Live, a collective water volume is discharged in the terrain. Overall, despite having similar objectives, the models are different in their working principles, capability and available features, as well as possess unique strengths and limitations.

6. Recommendation

In order to increase accuracy in damage assessment, the following is recommended:

- i. Update the mesh file so that it synchronizes with land use data as well as to include any recent changes in the terrain.
- ii. Calibrate the results obtained from the model with flood depth recorded during historical flood events that could be available in the form of field data measurements, written reports, photographs etc.

In order to increase effectiveness of blue-green measures, the following is recommended:

- i. Implement policies to encourage implementation of blue-green measures, also in private properties. LID solutions including green roofs, rain barrels, permeable pavements etc. are effective in reducing runoff volume significantly.
- ii. It is not advised to reduce the size of the proposed solutions since some of them are close to their critical limit. However, if it is not feasible to implement in such scale, it is advised to consider the flow coincidence effect in the downstream.

Recommendations for further studies:

- i. Construct finer size mesh specially in the area where solutions are proposed so that theoretically designed solutions could be replicated in the model accurately. (MSB, 2014) recommends resolution of 4m or less.
- ii. Perform flood modelling considering the effect of stormwater network. Recent hydraulic models for instance facilitate coupling 1D pipe models and 2D surface flow models. The method is "state-of-the-art" in terms of modelling pluvial floods.
- iii. Perform cost-benefit analysis to make economic assessment of the proposed alternatives.

Alternative measures for the study areas:

Hulan study area

- i. In zone two, it is plausible to seal the land to create a wetland and limit the flow into the road. This measure should be cost effective as well since it can be implemented with limited adjustment in terrain. It could significantly reduce the flow coincidence effect in the downstream area. However, increase in water depth in the surroundings could be troublesome for nearby residents. Possible effects of the solution to nearby resident should be studied.
- ii. In zone five, pond created next to meandering could be filled in by excavated material to avoid any possible mosquito problem to nearby residents. The existing meander upstream could be used as a pond similar to the one proposed in this study to collect excess water. In this way, the pond is pushed further upstream.

- iii. In zone four, it is advised to level out the wetland area so that the volume of water widely spreads in area to make maximum utilization of it.
- iv. In the downstream point, it is advised to upgrade the size of the drainage network since there is no more available space in area that could be utilized to collect the flooded water.

Berghultskolan study area

- i. Present results show parking lot in the school area is affected with water depth of more than 0.3 m. This could be avoided while still maintaining solution effective. Lowering playing field further by 20 cm, or elevating parking lot by the same height should solve the problem.
- ii. In zone two, where the upstream pond exists, it is advised to keep the natural creek flowing and use the pond only during extreme rainfall event when discharge exceeds certain level. This would not affect the natural flow of water while the solution would still function during extreme rainfall event. Implementing multistep channel similar to the one proposed in this study could be a good alternative.

7. Conclusion

The two study areas were shown to be highly vulnerable to urban flooding risk during the 100-year rainfall period for present land use scenario. In Hulan, over half of the buildings in the study area were found vulnerable to flooding in addition to some residential streets and part of a major highway. Similarly, in Berghultskolan, the school itself was the most vulnerable infrastructure in addition to few other surrounding houses (see section 4.1.1.). Hazardous zones that pose risks to human life were found in a dense settlement area in Hulan and at downstream point next to the school in Berghultskolan (see section 4.1.2.). Uncertainties associated with the vulnerability assessment regarding model calibration, analysis technique and limitations should be considered while analyzing and interpreting the results (section 5.2.).

Proposed blue-green measures were found effective to contain and divert stormwater runoff as well as control flood depth and velocity in both study areas (see section 4.4.). Tested during a 100-year rainfall event, the capacity of solutions in Hulan study area was adequate to control flooded water in the upstream area but not in the downstream area. Similarly, in Berghultskolan study area proposed solutions effectively controlled the flooded water in both upstream and downstream to mitigate the urban flooding risk during the 100-year rainfall event. During more extreme rainfall event (400 and 1000 years), most solutions proposed in Hulan study area and all solutions from Berghultskolan study area exceeded their design capacity to further increase flood risk at the downstream points. Changing the solution capacity by 10 percent changed the individual performance of the proposed solutions, but the effect at the downstream point was marginal.

Results from the two computer models MIKE 21 and SCALGO Live were very similar. Flood depth in SCALGO Live was generally higher than in MIKE 21 due to SCALGO Live not possessing the ability to include soil infiltration property in the model. SCALGO Live was simple to operate and at the same time extremely efficient during the preassessment study phase to gain a general overview of flood scenarios and effectiveness of proposed solutions. MIKE 21 on the other hand was at first technically challenging and required sophisticated knowledge to define and operate the desired model but it facilitated superior functionalities such as temporal variation of flow, soil infiltration capacity, soil roughness and possibility to include stormwater network in future. In conclusion, it was observed that MIKE 21 is a stand-alone tool, while SCALGO Live is not.

Further possibilities to modify the proposed solutions as well as possible use of alternative solutions are suggested in chapter 6. This chapter also lists suggestions for future studies that could further strengthen our understanding of vulnerability to flood as well as effectiveness of blue-green solutions.

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Appendices

Appendix A: Charts and tables

Charts and tables

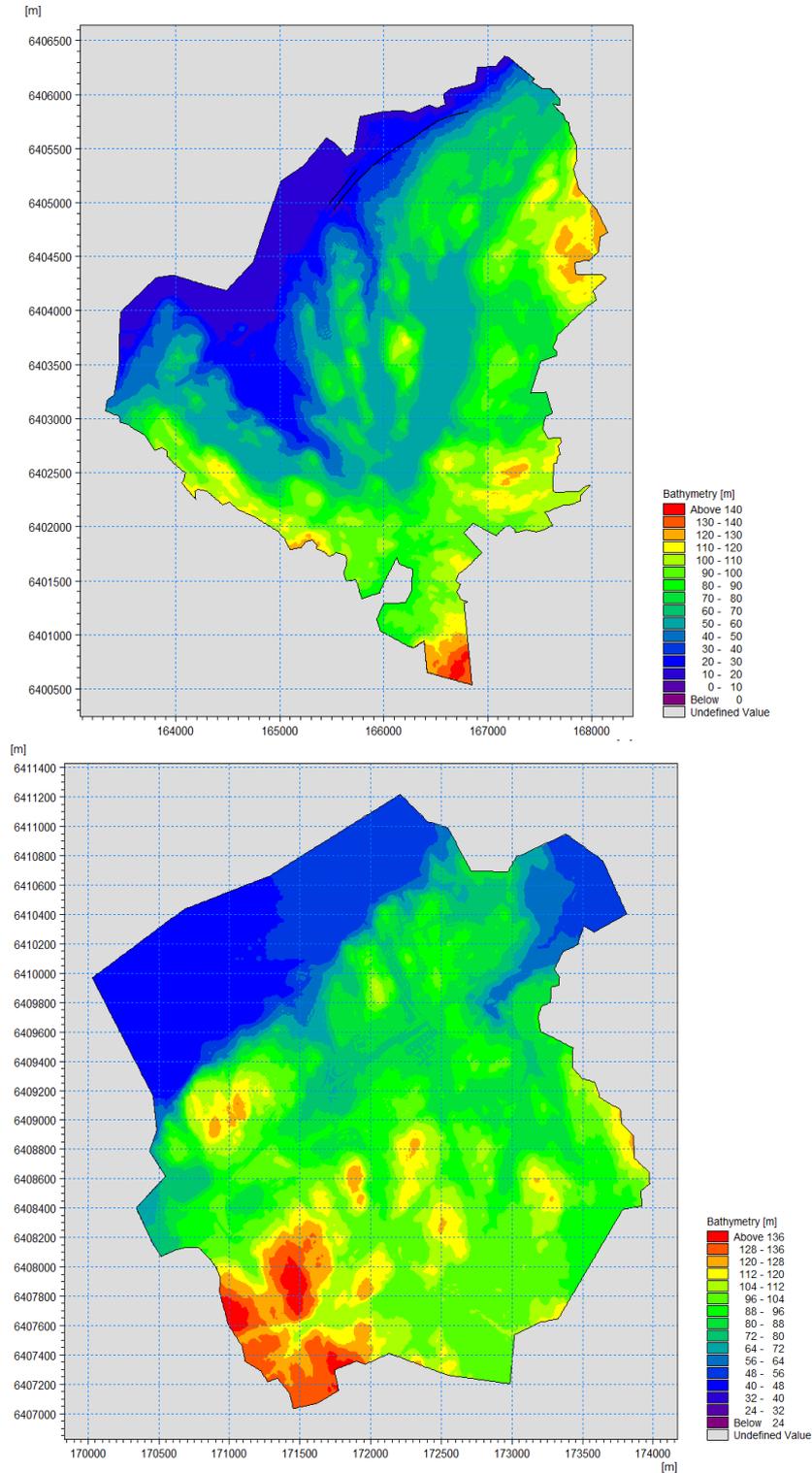


Figure A1 Flexible mesh file for Lerum (top) and Floda (bottom). Hulan lies within Lerum and Berghultskolan lies within Floda.

Table A1 Classification of impact of increasing flood depth on transportation system

| Depth | Consequences |
|------------|---|
| < 0.05 | No significant impact |
| 0.05 - 0.1 | Some trouble in accessibility |
| 0.1-0.3 | troublesome traction with ordinary vehicles |
| 0.3 - 0.5 | Not possible to get around with ordinary motor vehicles, the risk of major damage |
| > 0.5 | Not possible to get around with the fire trucks and rescue vehicles, the risk of life and death |

Table A2 Classification of impact of flood vulnerability score on human

| Class limit | Vulnerable age group |
|-------------|--|
| < 0.75 | no |
| 0.75 - 1.25 | children, elderly and physically challenged people |
| 1,25 - 2.5 | most people |
| > 2.5 | all |

Table A3 Details on spatial analyses performed in ArcGIS software

| Step | Critical infrastructure | | Vulnerable public space |
|------|---|--|--|
| | Buildings | Road | |
| 1 | Import maximum depth raster file into ArcGIS | | Import raster file of maximum water depth and flow into ArcGIS |
| 2 | Create a raster file with flood depth greater than 0.1 m | Create a raster file with flood depth greater than 0.3 m | use raster calculator tool to calculate a raster layer using Equation 4 |
| 3 | Convert Raster layer obtained from step 2 into vector image | | classify the obtained layer from step 2 into five categories from Table A2 |
| 4 | Find buildings present in the vector image | Find road in vector image | |

Table A4 Design parameters used for proposed solution

| Zone | Name | Size (average) | | | Area (ha) | Filling material volume (m ³) | Volume of excavation (m ³) | Design capacity (m ³) | |
|----------------------------------|-----------------------|----------------|------|------|-------------|---|--|-----------------------------------|--------------|
| | | L(m) | B(m) | H(m) | | | | | |
| Hulan study area | | | | | | | | | |
| 1 | Drainage canal | 420 | 2 | 1 | 0.08 | 356 | 5890 | 5534 | |
| 2 | Detention pond system | i | 75 | 40 | 2 | 0.3 | | 6140 | 18447 |
| | | ii | 75 | 40 | 1.6 | 0.3 | | 5536 | |
| | | iii | 165 | 34 | 1.3 | 0.56 | | 8590 | |
| | Terrain adjustment | | | | | 1819 | | | |
| | Total | | | | 1.16 | | | | |
| 3 | Detention pond | i | 150 | 13 | 2 | 0.2 | | 10795 | 24292 |
| | | ii | 55 | 35 | 2 | 0.2 | | 4956 | |
| | | iii | 150 | 17 | 2 | 0.25 | | 5462 | |
| | | iv | 70 | 20 | 2 | 1.4 | | 3079 | |
| | Total | | | | 2.05 | | | | |
| 4 | Raised road elevation | 186 | 5 | 1.7 | 0.06 | 2500 | | | |
| 5 | Dam | 200 | 6 | 2 | 0.12 | 3291 | | 145414 | |
| | Meander | 764 | 15 | 4 | 1.12 | 375 | 55414 | | |
| | Detention pond | 70 | 20 | | 1.4 | | 90000 | | |
| | Total | | | | 2.7 | | | | |
| Berghultskolan study area | | | | | | | | | |
| 1 | Detention pond system | i | 100 | 60 | 2 | 0.63 | | 10656 | 26473 |
| | | ii | 60 | 40 | 1.5 | 0.23 | | 3175 | |
| | | iii | 75 | 50 | 1 | 0.37 | | 10959 | |
| | | iv | 46 | 35 | 0.5 | 0.16 | | 800 | |
| | canal (i) | 291 | 2 | 2 | 0.06 | | 1811 | | |
| | cycling track | 260 | 3 | 1.5 | 0.08 | 1078 | | | |
| | canal (ii) | 225 | 0.4 | 0.4 | 0.01 | | 150 | | |
| | Total | | | | 1.54 | | | | |
| 2 | Detention pond | 180 | 30 | 2 | 0.54 | | 12321 | 7711 | |
| | Terrain adjustment | | | | | 4610 | | | |
| | Total | | | | | | | | |

Appendix B: Design and calculation of meandering

Available length from the road to dam in the flood zone five = 260m

Assume the meander is straight at the end (20m) and on either side of road (10m)

Available effective length = $250 - 20 - 10 - 10 = 220$ m

Assume a complete 1.5 cycle of meandering

Wavelength of one cycle (λ) = $220/1.5 \approx 146$ m

Channel length (L) =
$$\frac{\lambda * \text{valley slope}}{\text{channel slope}} = \frac{\lambda * 0.09}{0.05} = 276\text{m}$$

(Note: Channel slope designed for slope 5% while valley slope was calculated by measuring the gradient of the meandering plain at 5 different cross-sections)

Meandering is assumed to follow a sine wave (USDA, 2007) given by the sine equation

$$y = A\sin\omega x \quad (\text{Equation 5})$$

Where, $\omega = 2\pi/\lambda = 0.04$ and A is the amplitude,

$$y = A\sin 0.04x$$

$$\frac{dy}{dx} = 0.04A\cos 0.04x$$

The length of the curve is given by integrating the curve equation from the start and end of the cycle

$$\text{length} = r = \int_a^b \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx$$

$$L = \int_0^\lambda \sqrt{1 + (0.04A\cos 0.04x)^2} dx$$

$$276 = \int_0^{146} \sqrt{1 + (0.04A\cos 0.04x)^2} dx \quad (\text{Equation 6})$$

Equation 6 was solved for value of A in MATLAB, which was found as 51m

Then, equation 5 becomes $y = 51\sin 0.04x$ (Equation 7)

Equation 7 was integrated in the same interval as before to gain the planform for the sine wave which is shown in the Figure A2 below

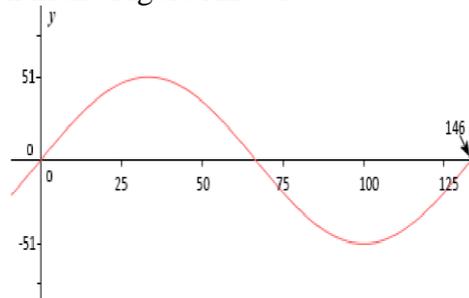


Figure A2 Planform for the flood meander. The horizontal and vertical axes show the distance along each axis

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF WATER AND ENVIRONMENT TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden



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