Urban Flood Risk Management of Østerå in Aalborg

Master's Thesis : VM10-2020

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AALBORG UNIVERSITY
STUDENT REPORT

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Synopsis:

This thesis deals with the management of the urban flood as a result of the opening of the new path of Østerå in Aalborg.
Firstly, a flood risk assessment to evaluate the hydraulic consequences of the new path and to estimate the likelihood of flooding has been made by implementing the new channel in Mike Urban 2017 software. To provide the initial conditions for the model, an observed data of Østerå, Limfjord and historical rain series data is used in order to improve the performance of the model. The result shows that the opening of the new channel has a positive effect on the flood cost and has a significant impact on the project area, especially by decreasing the flooded-area in the residential district of Karolinelund. Next, based on the assessment result, it has been investigated whether it is possible to provide a sustainable approach by implementing a control activities in order to handle the flood caused by the runoff-flow from the residential area. Two different scenarios have been implemented in Mike Urban Model, simulated and discussed. The first scenario is based on a passive control and the second one is based on an active (local) control. It has been found that both scenarios are sufficiently capable of reducing the flood and decrease the total flood cost.
Finally, the solutions are applied to the future condition to investigate the climate change impacts on the project area. From the result, it has been concluded that it is possible to handle the runoff water from the surrounding catchment through the implementation of the control scenarios in both the current and future condition.

Preface

This thesis is prepared as a part of the project module at 4th Master semester of Water and Environmental Engineering at Aalborg University. The report is written by Saad Allah Ghassan Kassam of VM10 in the period from February 2020 to June 2020. The overall objective of the thesis is to evaluate the consequences of the opening of the new path of Østerå in Godsbanearealet and Karolinelund in the municipality of Aalborg and to produce flood risk maps showing a likelihood of flooding.

Appreciation is addressed to supervisors Søren Liedtke Thorndahl and Rasmus Nielsen for good collaboration, response on the forwarded mails and questions and for numerous fruitful meetings and for their enthusiastic guidance and precious advises throughout the study.

I would like to thank my parents for their love and support, especially within my last months of graduate studies.

Reading Guide

The project consists of a main report with appendix. Appendix A to D can be found in the report while appendix E is found as an electronic appendix attached to the report. For appendix E in the report a short description of each electronic appendix can be found.

In the report the Harvard method is used as reference method. References will be in brackets with author followed up by year of publication, for example [Butler et al., 2018]. The references are either placed within or after the section where they are applied. When referring to a web-page either the author or the name of the web-page is specified, for example [Forsyning, 2014] .

The references in the bibliography are written in alphabetical order. Equations, tables and figures are numbered according to the chapter or appendix with number or letter and the order of presenting them, for example figure 7.10 is the tenth figure in chapter 7.

Saadallah

Saad Allah Ghassan Kassam

Danish summary (Dansk resumé)

Dette projekt omhandler håndteringen af urban oversvømmelse som et resultat af åbningen af den nye kanal i Østerå i Aalborg. For det første er der foretaget en vurdering af oversvømmelsesrisikoen for at evaluere de hydrauliske konsekvenser af den nye kanal og for at estimere sandsynligheden for oversvømmelse. Dette er gjort ved at implementere den nye kanal i Mike Urban 2017-software. Modellens startbetingelser er bestemt ved brug af målinger fra Østerå og Limfjorden samt historisk regndata. Dette er gjort med henblik på at forbedre modellens ydelse. Resultatet viser, at åbningen af den nye kanal har en positiv effekt på oversvømmelsesomkostningerne og har en betydelig indflydelse på projektområdet, især ved at mindske det oversvømmede område i boligområdet i Karolinelund. På baggrund af vurderingsresultatet er det dernæst undersøgt, om en bæredygtig løsning er mulig ved implementering af en kontrolsaktivitet for at håndtere oversvømmelsen forårsaget af afstrømningen fra boligområdet. To forskellige scenarier er implementeret i Mike Urban modeller. Disse scenarier er simuleret og diskuteret. Det første scenarie er baseret på en passiv kontrol, og det andet er baseret på en aktiv (lokal) kontrol. Det er konstateret, at begge scenarier reducerer både oversvømmelse og de totale oversvømmelsesomkostninger tilstrækkeligt. Afslutningsvis er løsningerne analyseret under fremtidige forhold for at undersøge effekten af klimaforandringer på projektområdet. Med udgangspunkt i resultatet er det konkluderet, at det er muligt at håndtere afstrømmet regnvand fra det omkringliggende opland i både nutidige og fremtidige scenarier ved implementering af kontrolscenarier.

Contents

Symbol References

Abbreviation	Definition
CBA	Cost Benefit Analysis
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
DMI	Danish Meteorological Institute
IDA	Society of Danish Engineers
RTC	Real Time Control
WPC	Water Pollution Committee

Symbol	Unit	Explanation
A	[m^2]	Cross section
A_v	[m$^2/s$]	Horizontal eddy viscosity
A_0	[ha]	Area
b	[m]	Width at the water surface
Flood Depth	[m]	Maximum Flood Depth
F_u and F_v	[kg.$m^{-1}.s^{-2}$]	The horizontal stress
g	[m$^3.kg^{-1}.s^{-2}$]	The gravitation
h	[m]	Water level
h_0	[-]	Constant
$LTS_{criteria}$	[m$^3/s$]	Long Term Statistics
M_R	$\frac{\mathrm{m}^{1/3}}{\mathrm{s}}$	Average Manning Roughness in the down stream
N	[-]	Constant
Q	[m$^3/s$]	Discharge
q	[m$^3/s/m$]	Discharge per pipe meter
R_d	[mm]	Rain depth
R_f	[-]	Hydraulic reduction factor
S	[m$^3/s$]	The storage
S_f	[-]	The friction slope
S_0	[-]	The bottom line slope
T	[min]	Time
t	[sec]	Time
u, v and w	[m/s]	The velocity components in x,y and z direction
x, y and z	[m]	The Cartesian coordinates

I Introduction

1. Introduction

Until recently, there has been a focus on flood world wide, as more cities are becoming increasingly vulnerable to flooding because of rapid urbanization, installation of complex infrastructure, and changes in the precipitation patterns caused by anthropogenic climate change [Willems et al., 2012]. Climate change is also an important and discussed subject during these past years. Even though the climate change will has a severe impact on the function of urban drainage system, where rain events will intensify and water level of receiving waters will rise but still connecting climate change to floods can be a tricky endeavor. The limited data on the floods in the past makes it difficult to measure them against the climate-driven trends of floods today.

Floods are considered an important issue due the major damage they can cause and claiming a high toll both in terms of economic damage and fatalities. From 1980 - 2005, 84% of all disasters were related to hydro-meteorological factors, with floods as the main factor causing disasters [Kjølby, 2016] . A changing climate is likely to increase the risks for many regions. Floods can cause injury and loss of life, considerable economic costs, and damage to the environment and cultural heritage. Serious floods have become more frequent in Europe. In recent years, more than twice as many flash floods of medium to large magnitude have been registered as in the late eighties [AUDITORS, 2018]. Figure 1.1 shows an example of the flood occurs in Denmark on the 2^{nd} of July 2011, where the insurance companies recorded a damage in Copenhagen up to Millions kroner [Miljoministeriet, 2013].

Figure 1.1: The observed flood on 2^{nd} of July 2011 in Copenhagen [DMI, 2011].

In 2008 the municipality of Aalborg released a plan to operate a major change in Godsbanearealet in the future. The main concept of the plan is to open the new path of Østerå from Jernbaneparken to end up in the Limfjord [Aalborg Kommune, 2009]. The area is shown in figure 1.2. The objective of the municipality is to reinvigorate the urban life with different activities and to increase the overall attractiveness of the Godsbanearealet district [Aalborg Kommune, 2010]. Such a change synthesis interaction between the drainage system and the new path of Østerå leading to new hydraulic condition.

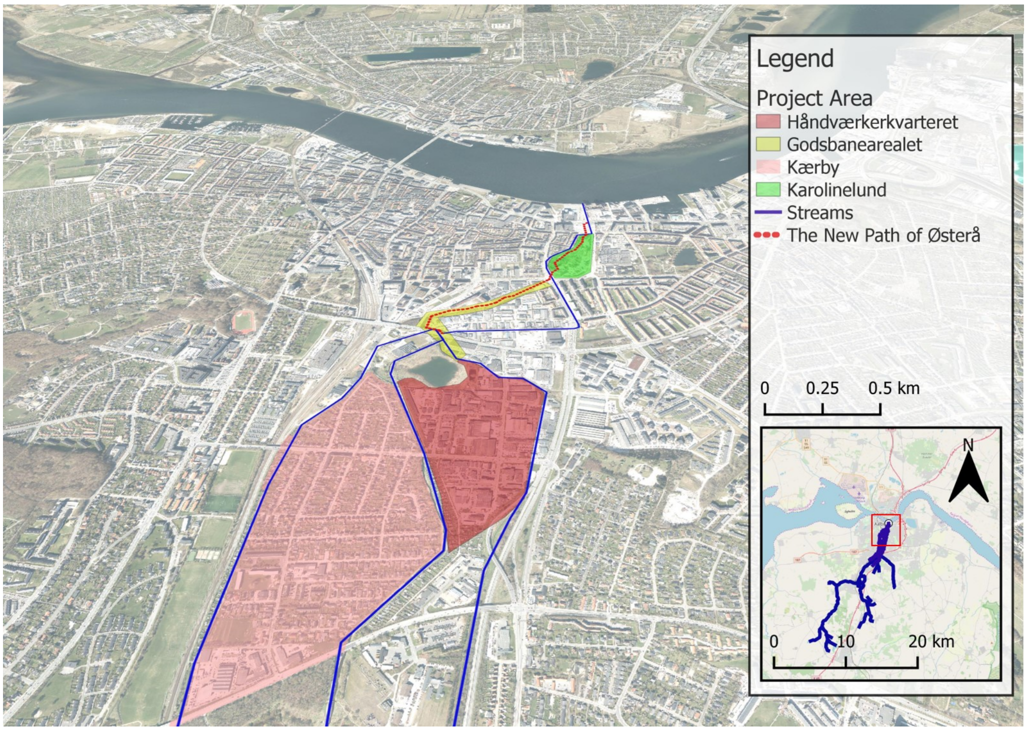

Figure 1.2: Project area and the locating of the new path of Østerå.

A separation between wastewater and stormwater was initiated for new systems during the 1970's and this work is still ongoing. Aalborg municipality launched a goal to separate the entire sewer system before the year 2100 and preferably sooner[Aalborg Forsyning, 2009]. The separate sewerage strategy is considered to be fundamental in relation to adapting the sewerage system to the increased precipitation amounts of climate change [Miljo og Energiforvaltningen, 2016]. Such a change will increase the volume of stormwater loads diverted to local receiving waters. Usually, in urban or developed areas the stormwater runs over the pavement and parking lots before flowing into a nearby river or stream. Impervious surfaces increase the amount and speed of water entering rivers. As a consequence of impermeable surface stormwater travels rapidly, resulting in the flow in the network to appear and die at a fast pace generating peaks. These peaks can seriously challenge the hydraulic capabilities of the network and the receiving water bodies and can give rise to flood events and increase in the severity and frequency of floods [Butler et al., 2018]. As a consequence, urban drainage networks must accommodate for the needs of both the environment and the humans living in it, making their functionality a crucial aspect in the development of urban areas.

Recently, extreme rainfall events were recorded in many places in Denmark. These events caused several major pluvial floods due to insufficient capacity of storm drainage systems. In additional to the limited hydraulic capacity of drainage system, the area off case study characterized by low elevation and high groundwater level as well as limited hydraulic capacity of stream network [Rasmuse Nielsen, 2019] as illustrated in chapter 2. Based on that, a hydraulic study must therefore be conducted in order to evaluate the consequences of this new path, particularly concerning the potential risk of flooding.

2. Description of the Area

This chapter includes a brief overview of the project location, The municipality of Aalborg, its topography and its urban drainage system.

2.1 Location

Aalborg municipality is located in the northern part of the Jutland peninsula in Denmark as shown in figure 2.1, covering an area of about 111 km^2, and serving a population of approximately 135.000 inhabitants [Rasmuse Nielsen, 2019]. The project site is focus on Kærby which characterized as a residential area, Håndværkerkvarteret which is more industrial area, Godsbanearealet and Karolinelund. The Godsbanearealet has not been used for the past 10 years and now it is covered with grass and construction materials especially the railway materials [Polyform et al., 2010]. The municipality is intent to reinvigorate the urban life with different activities and to increase the overall attractiveness of the area and among the several changes is to open the the new path of Østerå as mentioned in chapter 1 .

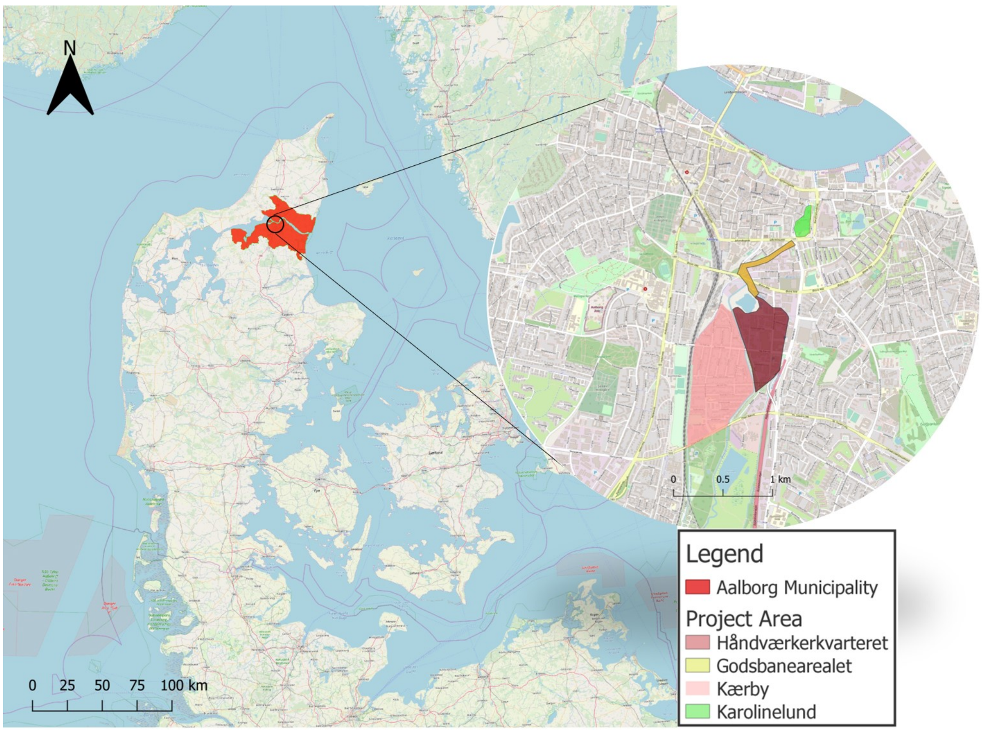

Figure 2.1: Location of Aalborg municipality in national scale [Brinkhoff, 2019] and the project area in municipal scale.

2.2 Precipitation and Topography of the Area

In general the climate in the case study is characterized by cool summers and mild winters and a yearly precipitation of 750 mm and an average temperature of 8.5 °C. The project area is located on a site has a low elevation and situated between two hilltops towards respectively East and West as shown in figure 2.2 which make the area vulnerable to attract the runoff flow from the surrounding catchments, but the elevation is not the main reason behind the flood. The terrain heterogeneity may have an influence on water dynamics, especially when a flood occurs, but the urban flooding is more likely linked to the hydraulic capacity of the outgoing streams. The high groundwater table of 1 m under the terrain [og Fødevareministeriet Miljøstyrelsen, 2017] and limited hydraulic capacity of older combined sewer system and the stream network[Rasmuse Nielsen, 2019] causes the critical condition and explain why the area is a matter for flood issues.

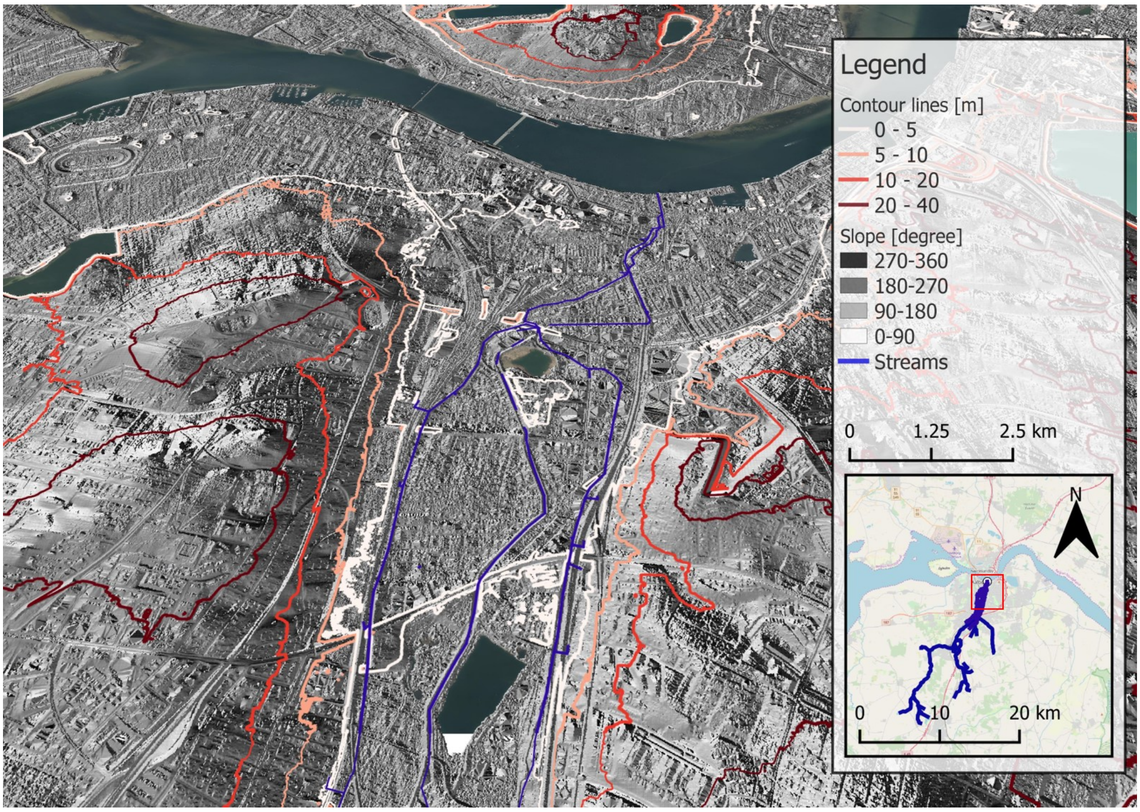

Figure 2.2: The elevation map in the project site .

2.3 Overview of Sewer System

In regard to the drainage system in Aalborg municipality, Aalborg Forsyning has the responsibility for managing all the wastewater system within it. It is their responsibility to build, operate, manage, improve and develop sewerage and treatment plants in line with developments in the municipality of Aalborg [Forsyning, 2014].

Currently, the sewer system is a mixed between combined system and separated system as can be seen in figure2.3. The daily flow from residential and industrial area as well as the normal runoff from the impermeable area are pump to Wastewater Treatment Plant in the West of Aalborg by several pumping station, which after to be discharged to the Limfjord.

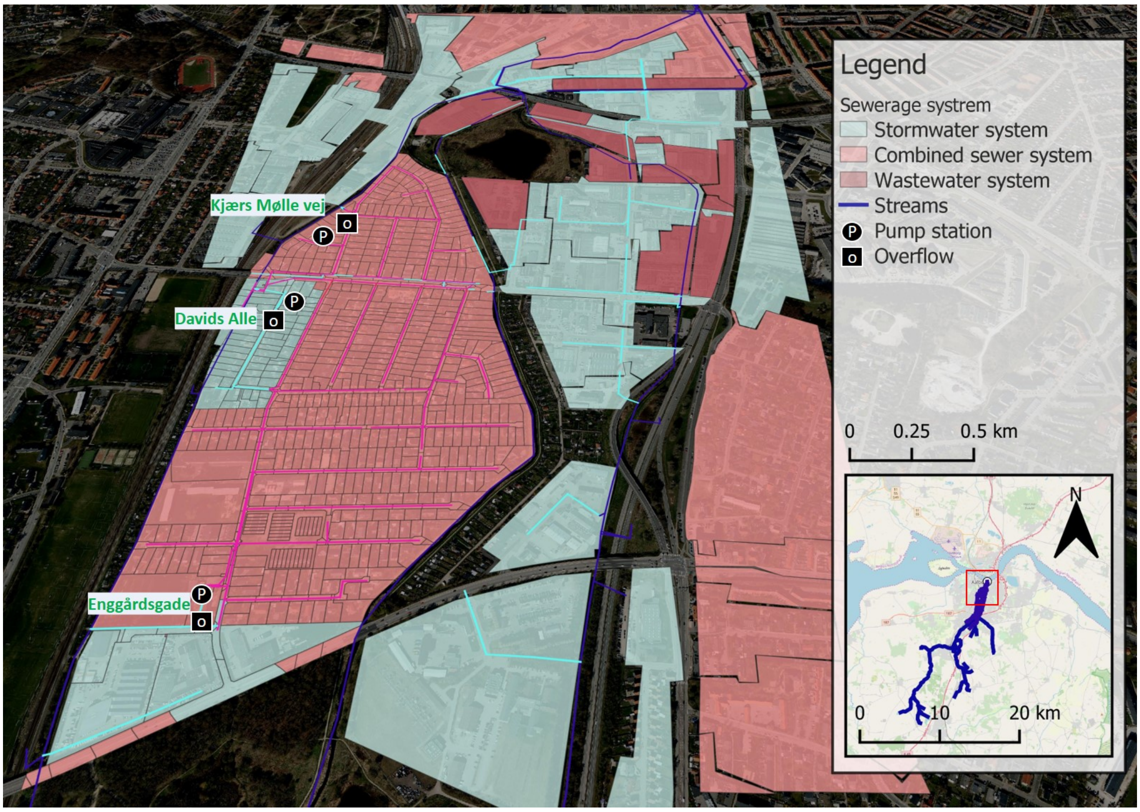

Figure 2.3: The drainage system type in the project area [forsyning, 2008].

From figure 2.3, it can be noticed that the area is consists of different sewer catchments type, these catchments are connecting to three pump stations associated with overflow buildings at Enggårdsgade, David Allé and Kjærs Mølle Vej. The wastwater transport through the catchments to the pump station by gravity before it is pumped outside the project area to the wastewater treatment plant in the west of Aalborg. In case of the overflow in the drainage systems due to an extreme rain events, the overflow building discharge the wast water directly to Vestre Landgrøft.

3. Problem Statement

The opening of the new path of Østerå in Godsbanearealet and Karolinelund in the municipality of Aalborg is intended to reinvigorate the urban life with different activities and to increase the attractiveness of the area. The overall objective of this project is to evaluate the consequences of such a change and to produce flood risk maps showing a likelihood of flooding. The challenge is to determine the probable impact on the study case regarding the opening of the new path of Østerå and to evaluate whether this path will change the current situation in Godsbanearealet, Karolinelund and the district of Kærby as illustrated in figure 3.1. When establishing the new path and detecting the possible flood, the need for flood risk management plans to handle the area that is exposed to flood is arising. Two sustainable approach by using a control activity will be implemented to minimize the potential flood and optimize the drainage system. The first scenario will be based on a passive control and the second one will be based on an active (local) control. The First approach will take the volume of the current path into consideration in order to reuse the path during the extreme rainfall events and investigate whether it can be helpful in reducing the potential flood. While the second approach will be based on the implementation of a new basin in the project area to handle the runoff flow from the surrounding catchment during the most extreme rainfall events . Additionally, applying a climate projected rain series in order to represent extremes precipitation in the future condition.

What are the hydraulic consequences of the opening of the new path of Østerå concerning the risk of flooding and is it possible to provide a sustainable approach to control the flood caused by the runoff-flow in order to reduce the risk?

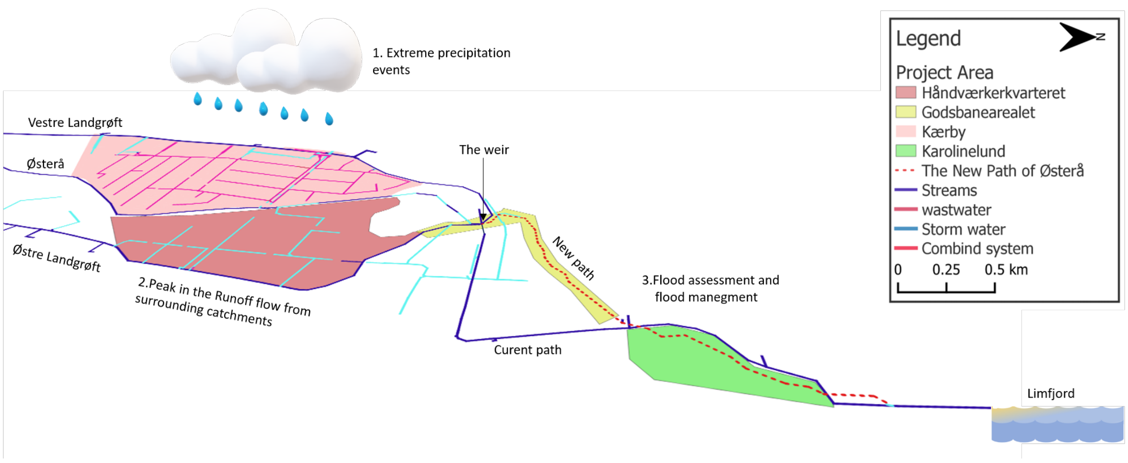

Figure 3.1: Illustration of the problem statement from source to the outlet in Limfjord.

4. Strategy

The main focus of the description of the project area as illustrated in chapter 2 is understanding the hydrological conditions where it is important to establish that the drainage system is more than just manholes and pipes in the ground. The interface between the sewer system , Østerå and Limfjord is the key aspect of the exceeding flow that cause the flood. Calculating the degree and extent of such interaction is complex and resource consuming but recently the modelling software has made it easier to assess. In this project the assessment of the potential flood is performed through the MIKE modelling packages from DHI, where hydraulic modelling of the urban drainage system is carried out with MIKE FLOOD and results analyzed with special focus on the observed flood area, flood depth and then the damage cost . In order to improve the performance to fulfill the aim of the model an observed data from Østerå and Limfjord are used as boundary condition. The structure of the project is as seen in figure 4.1

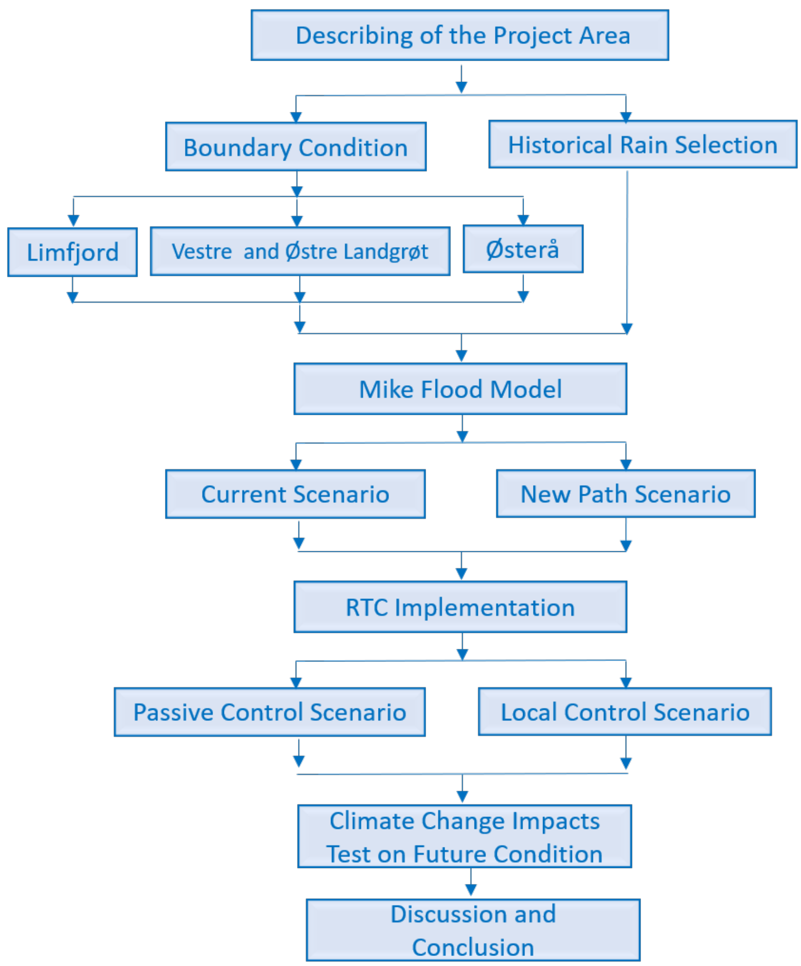

Figure 4.1: Illustration of the strategy.

As it can be seen from figure 4.1, the project area is described first in chapter 2 and the definition of the boundary condition together with the selection of the historical rain events is followed in chapter 5. The historical rainfall data set together with a coupled 1D/2D surface and network model allows to analyze and assess the potential flood in the project area as illustrated in chapter 6. As soon as the flood is detected, the implementation of the control scenarios is used to manage the flood in chapter 7. Finally, climate Projected rain series is applied to represent the future conditions in chapter 8.

II Input Parameters and Modelling

5. Boundary Conditions and Precipitation

The project area consists of three main streams Vestre landgrøft, Østerå and Østre landgrøft, these streams receive the overflow from the surrounding contributing catchments during the extreme rainfall events. The contributing catchments and the source of the streams can be seen in figure 5.1. The focusing site of the case study is located in the region where these streams meet in a weir as illustrated in the figure 5.1. The weir site is shown in figure 5.2 and 5.3.

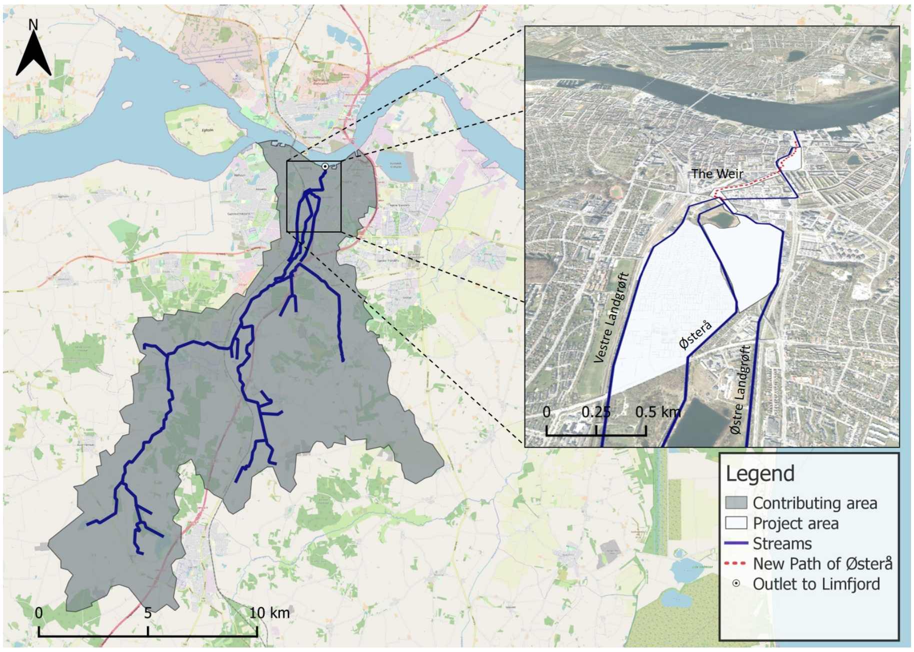

Figure 5.1: The contributing catchment and the main participants [Rasmuse Nielsen, 2019]. The red rectangle shows the focused area.

Figure 5.2: The inlet point in the weir to the new path of Østerå. The photo was taken in November 2019.

Figure 5.3: A view of the weir where the three streams meet. The photo was taken in November 2019.

In order to have a full understanding of the hydraulic processes and the interactions between the rivers, sewer system and the limefjord that affect the hydraulic condition of the case study, a field measurements for each phase based on previous studies from [Rasmuse Nielsen, 2019] are used to determine the annual pattern and to clarify the seasonal variation. These boundaries is used later as an input to Mike Urban model in chapter 6.

5.1 Østerå Boundary

Østerå originates in Rebild Municipality and runs northeast of Støvring along with Guldbæk slightly south of Dall Villaby to end up to Limfjord and it measures approximately 15 kilometres long. The water level measurements value of Østerå is presented on figure 5.4.

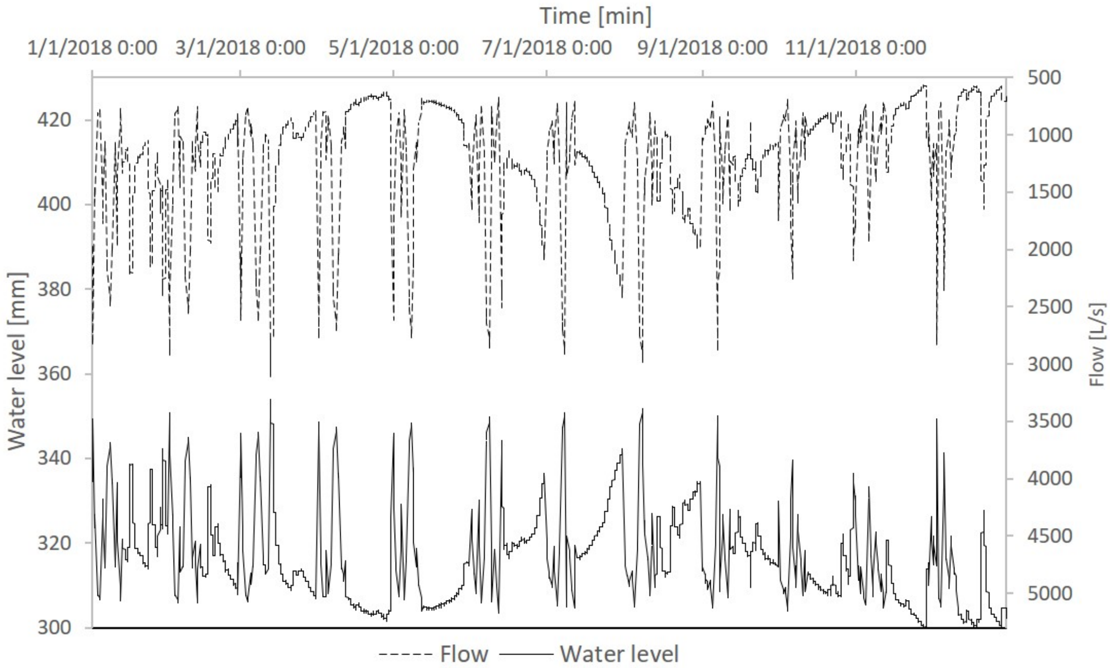

Figure 5.4: The flow boundary and the water level in Østerå.

Figure 5.4 shows the measurements data from January 2018 to January 2019. The measurements were executed from January 2000 to January 2016 and from April 2017 to march 2019 and the whole time series data is shown in appendix A.1. The flow boundary is generated from the water level in Østerå , where there is a linear relationship between flow and waterlevel based on equation 5.1.

$$Q = A.(h - h_0)^N \tag{5.1}$$

Where:	Q	Discharge	[m^3/s]
	h	Water level	[m]
	h_0	Constant	[-]
	N	Constant	[-]
	A	Cross section	[m^2]

As it can be noticed from the figure above, the amount of water that is discharged by streams decreases during summer compared to winter, where higher water level is expected in winter compared to summer. Since there are seasonal variations in the amount of rainfall, this results in more considerable a pattern visible in both stormwater throughout the year .[Butler et al., 2018]

5.2 Vestre and Østre Landgrøft

Alongside the part of Østerå there are two land trenches, respectively Vestre and Østre landgrøft. The Vestre landgrøft is partially piped and has an outlet in Østerå just before Kjærs Mølle as can be seen in figure 2.3. Vestre landgrøft has an outlet in the river just after the fishing stairs and it receives a significantly larger amount of overflow during the rainfall events than Østerå. For a return period of 10 years, the flow in Vestre Landgrøft was approximately 3800 l/s (730 l/s/km^2) while in Østerå it was approximately 1000 l/s (7,7 l/s/km^2).[Aalborg Kommune, 2016] This variation is due to the topography of the contributing catchments as has already been mentioned in chapter 2. Since the flows in Vestre landgrøft and Østre landgrøft is almost zero during the dry weather, a fixed flow of 0.055 m^3 and 0.015 m^3 respectively is chosen as a boundary condition. Where these values effects can be neglected compared to the annual flow of Vestre landgrøft and Østre landgrøft that received from the runoff-flow from the surrounding catchments.

5.3 Limfjord Boundary

The Limfjord has a significant impact on the surrounding area. According to a study made by the Danish Hydraulic Institute (DHI) the water level during normal storms rises by 26 cm and this causes flood issues in the surrounding area and due to the climate change this value is expected to increase by 15 to 60 cm.[Christensen, 2015] The effect of the climate change is discussed in chapter 8. The annual waterlevel of limfjord based on field measurements is shown in figure5.5.

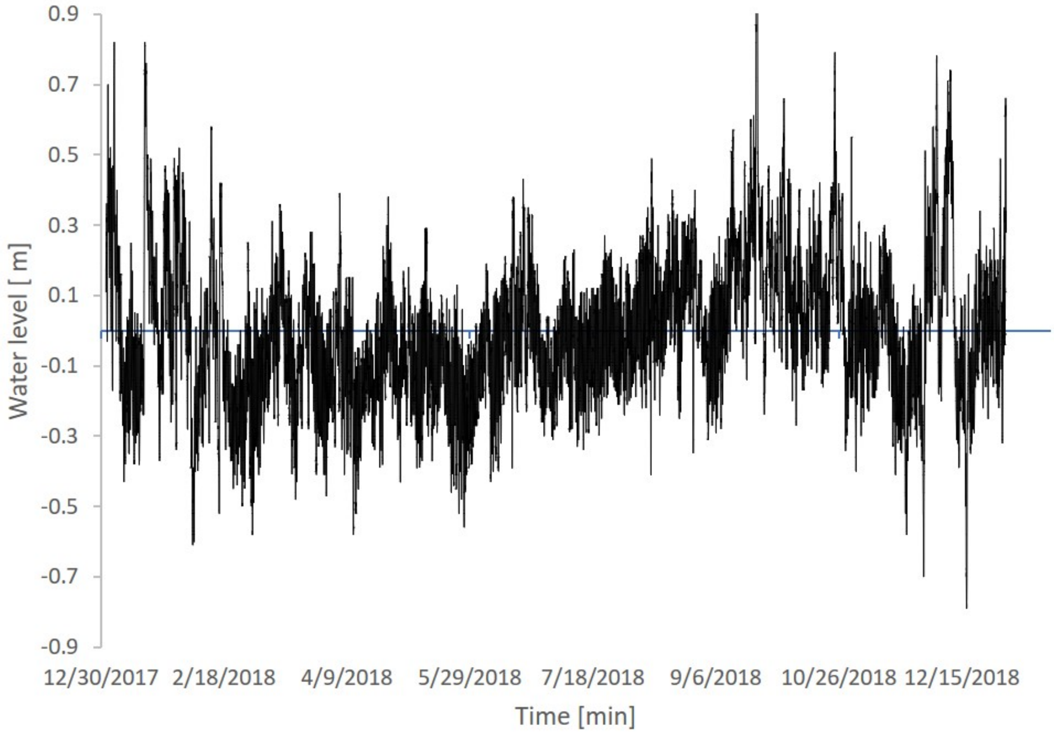

Figure 5.5: The water level in limjford.

Despite the steams and the limfjord show a higher water level in the winter the interactions between the streams , sewer system and limfjord is still fairly complex. Generally, the process that contributes the most to the increase in the water level in the limfjord is the wind, while the overflow that is caused by extreme rain events is more likely the reason of the high water level in the streams.

5.4 Precipitaion

As already noticed from figure 2.3, urban drainage system deals with both wastewater and stormwater. Some area has a combined system while another has a separated one. Most stormwater is a result of rainfall events and other forms of precipitation such as snow, hail and drizzle but the heavy rain is the most significant among them.[Butler et al., 2018] Observing rainfall data provides historical records which allow to understand the relationships between rain event properties such as particularly, intensity, frequency and duration. Rain gauges are the most common device for measuring rainfall intensity and they are operated by the Danish Wastewater Pollution Committee (WPC) together with the Danish Meteorological Institute (DMI), where there are around 150 different rain gauges spread all over the country. Recording gauges are able to provide a continuous record of rainfall by using a balanced reservoir consisting of two miniature compartments. In this project, a 30 year long rainfall measurement dataset from Østerport gauge station is used, as it is the closest rain gauge in the case study and therefore it is expected to be the most representative for the precipitation in the area, but one of the other stations could also have been applied. The location of the rain gauges in Aalborg and the chosen one is illustrated in figure 5.6 and the historical rainfall time series is shown in figure 5.7.

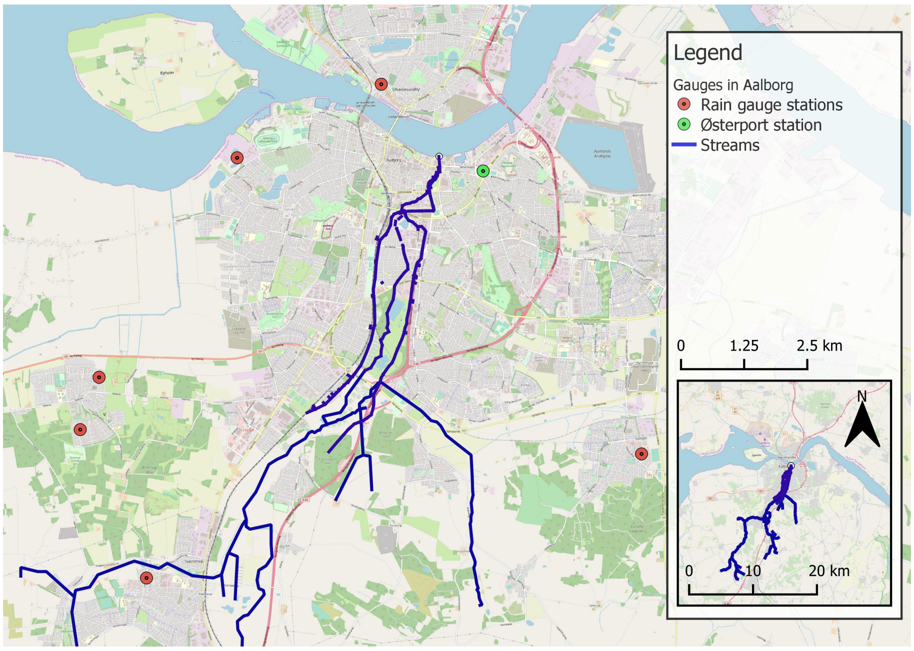

Figure 5.6: Aalborg rain gauge stations.

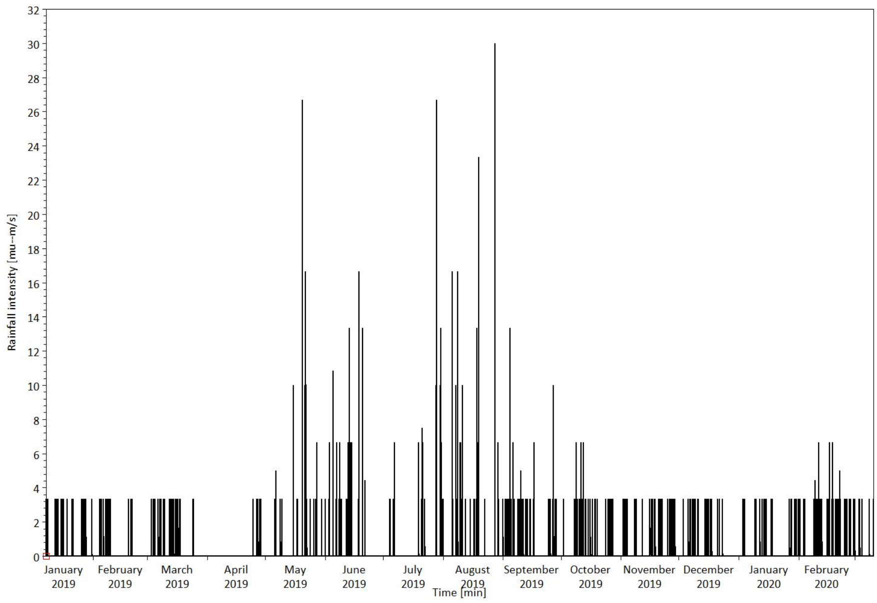

Figure 5.7: Historical rainfall series of period from 1-1-2019 to 10-3-2020, measured at Østerport rain gauge.

The whole historical rainfall data that is measured at Østerport rain gauge can be seen in appendix A.3.

In order to evaluate and analyze the potential flood in the new path of Østerå based on the historical rain data, a few single storms are chosen to present the most extreme events. While the rest are neglected to avoid the time consuming during the model simulation, since these events do not serve the aim of the project. The selection must ensure the variability of rainfall types, from extreme high peak storms with a short duration to more moderate rainfall with longer duration, and this can be applied in Mike Urban model (chapte 6) by using the Long Term Simulations module through combination of two criterion's:

- The threshold : the total flow or the runoff volume from the contributing catchments to the drainage system. The criteria is calculated from equation 5.2.

$$Threshold_{criteria} = \frac{R_d \cdot A_0 \cdot R_f}{T} \tag{5.2}$$

Where:			
	$Threshold_{criteria}$	The threshold	[m^3/s]
	R_d	Rain depth	[mm]
	A_0	The area	[ha]
	R_f	Hydraulic reduction factor	[-]
	T	Time	[min]

- The duration: characterized as the amount of time that runoff surpassed the threshold.

A matrix of 3 different thresholds 5 , 15 and 22 m^3/s and 3 different duration 10, 30 and 60 min is applied in the model. The result shows 295 events can be seen in Electronic appendix E.1 The final step for rainfall event selection is performed through the focusing on the accumulated rain depth. This step minimized the rainfall event number to 13 events with total depths larger than 20 mm. and the final list that used in this study is shown in the table 5.1 and the accumulated value for the selected events in the table is shown in figure 5.8.

Table 5.1: The final selected rain events.

Event number	Starting date	Ending date	Duration	Accumulated - Flow (mm)	Yearly Return Period
1	6/22/1998 0:36	6/22/1998 10:04	09:28:00	83	31
2	8/14/2006 23:47	8/15/2006 13:46	13:59:00	76	15.5
3	9/15/1994 5:22	9/15/1994 18:38	13:16:00	59.6	10.33
4	7/29/1998 21:19	7/30/1998 8:26	11:07:00	51	7.75
5	6/2/2001 8:16	6/3/2001 11:49	27:33:00	49.8	6.2
6	8/4/2008 4:27	8/4/2008 18:58	14:31:00	46.8	5.17
7	6/18/2002 12:16	6/18/2002 18:35	06:17:00	45.6	4.43
8	7/10/2002 20:39	7/11/2002 0:35	3:56:00	43.4	3.88
9	5/21/2019 23:08	5/22/2019 9:47	10:39:00	42	3.44
10	9/8/1994 22:58	9/9/1994 15:18	6:20:00	40.6	3.1
11	8/26/1996 12:27	8/26/1996 13:57	01:30:00	40.2	2.82
12	8/6/2012 5:29	8/6/2012 9:51	04:22:00	37.2	2.58
13	6/9/2017 13:47	6/9/2017 19:50	06:03:00	28.2	1.19

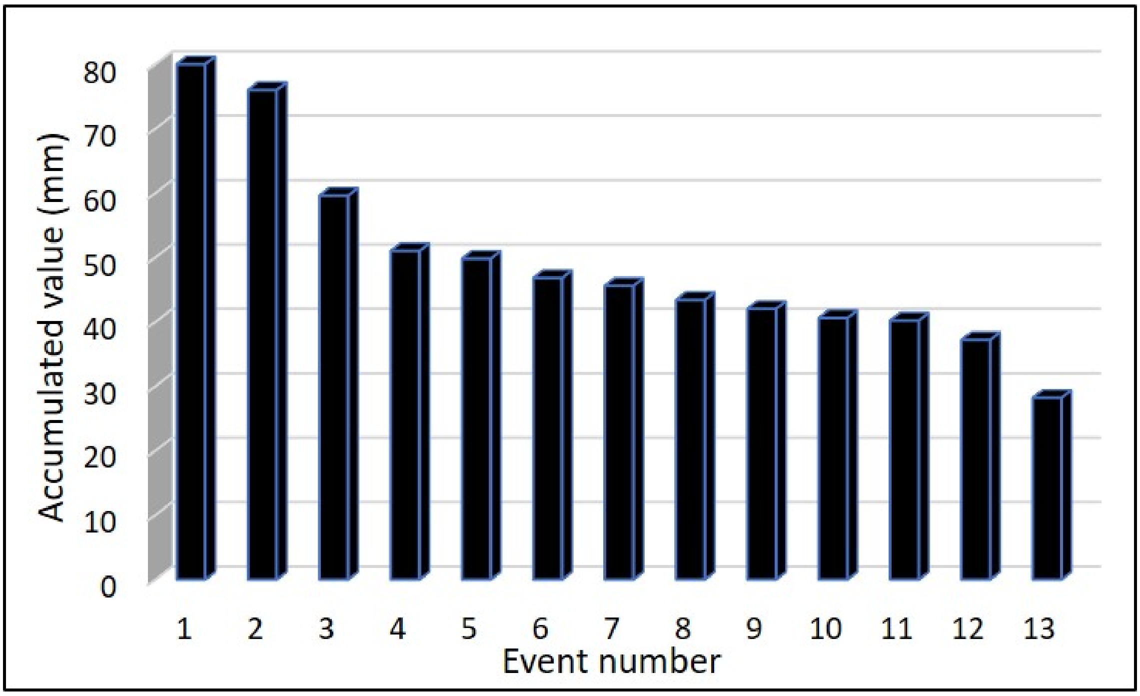

Figure 5.8: The accumulated value for the selected events in the table 5.1

6. Urban Drainage and Flood Model.

This chapter contain an introduction to Mike Urban Model which used to simulate the urban drainage system, model set up, the overland flow (Mike Flood) and scenarios.

6.1 Introduction to Urban Drainage Model

Mike Urban has two working modes: water distribution for drinking water and a collection system for the drainage system which is related to the type of this study. In turn,the collection system can be modelled with either the Storm Water Management Model (SWMM5) engine or the MOUSE engine. The model which is used in this project is the Modeling of Urban Sewer (MOUSE), but the other model can also be applied. The MOUSE model consists of three parts: the hydrological surface, the hydraulic surface runoff model and the hydraulic pipe flow model. In regard to the hydrological surface model a linear relationship between the runoff and the precipitation to determine the runoff volume from the contributing catchments, where the runoff volume is calculated by subtracting the percentage of impervious area (based on hydrological reduction factor and initial loss) from the precipitation. The hydraulic surface runoff model predicts the water routes and the transportation of water from the surface to the manholes. Mike urban has many methods to model this part but Time-Area Model (based on the time of concentration) is used in is this study. The hydraulic pipe flow model transports the water in the sewer system and this transportation of water is based on the one dimensional Saint Venant equations (Shallow water equations) which describe the incompressible flow below a pressure surface in a fluid that are commonly used to model transient open channel flow and surface runoff. as can be seen in equations 6.1 and 6.2.[Søren Thorndahl, 2008]

$$q = \frac{\partial Q}{\partial x} + b.\frac{\partial y}{\partial t} \tag{6.1}$$

Where:

q	Discharge per pipe meter	[m$^3/s/m$]
Q	Discharge	[m$^3/s$]
x	Flow axis	[m$^3/s$]
y	Depth axis	[m]
t	Time	[sec]
b	Width at the water surface	[m]

The saint Venant equations also consist of the law of conservation of momentum (second law of Newton),

$$\frac{\partial Q}{\partial x} + \frac{\partial \frac{Q^2}{\partial A}}{\partial x} + g.A.\frac{\partial y}{\partial x} = g.A.S_0 - g.A.S_f \tag{6.2}$$

Where:			
	A	Cross section area	[m^2]
	S_f	the friction slope	[-]
	S_0	the bottom line slope	[-]
	g	the gravitation	[$m^3.kg^{-1}.s^{-2}$]

The 1D saint Venant equations are used extensively in computer models such as SWMM5, Mike 11, Mike She and Mike Flood. Where this equation can be used in many applications like the flood routing along rivers, storm runoff in overland flow and dam break analysis, etc.

6.2 Mike Urban Model Set up

A complete hydrodynamic model of the study area has been provided by [Rasmuse Nielsen, 2019], and all hydraulic model of the drainage system in this project is carried out with mike Urban package 2017. The model setup consists of 870 catchments covering an area of 142 ha. with 600 manholes and 635 pipes spread within the catchment area. The model also contains 20 storage basins, 9 pumps and 15 outlet discharge points. The model set up is illustrated in figure 6.1

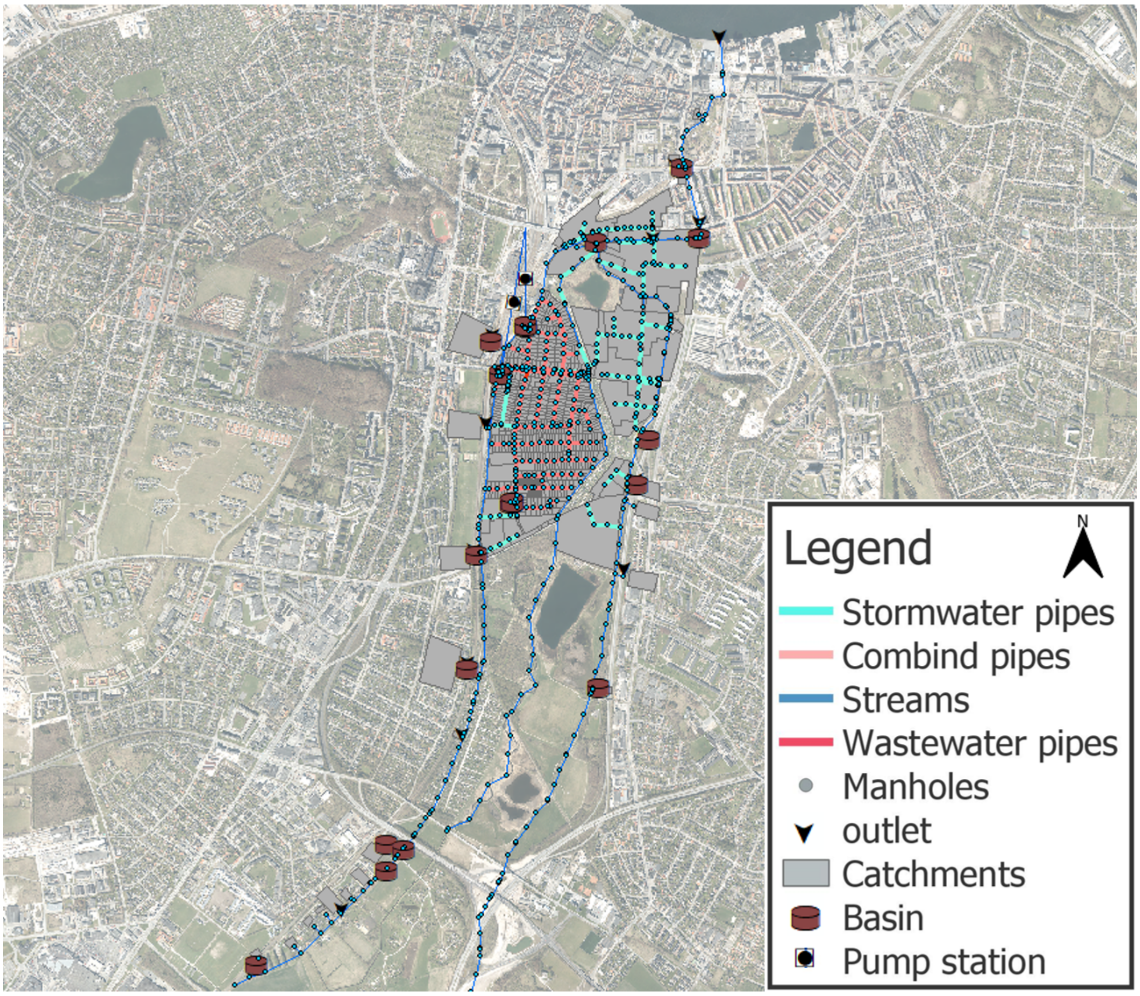

Figure 6.1: Mike Urban Model set up.

In regard to the new path and in order to connect the new path to the urban drainage system in Mike model, The implementation is based on the following assumptions. The dimensions of the new path is assumed as displayed in figure 6.5. This assumption has been based on some architecture plan which shows a variation of the cross section along the new path where most of the sections show two stages: the first stage is an open channel and the second one is for bikes pedestrians and picnic places as shown in figure 6.2 .[Aalborg Kommune, 2016] and [Arkitekter, 2015]. The dimensions of both the current path and the previous part of Østerå also has been taken into account during the selection as can be seen in figure 6.4 and 6.3. A fixed cross section along the new path has been chosen and the dimensions are shown in figure 6.5.

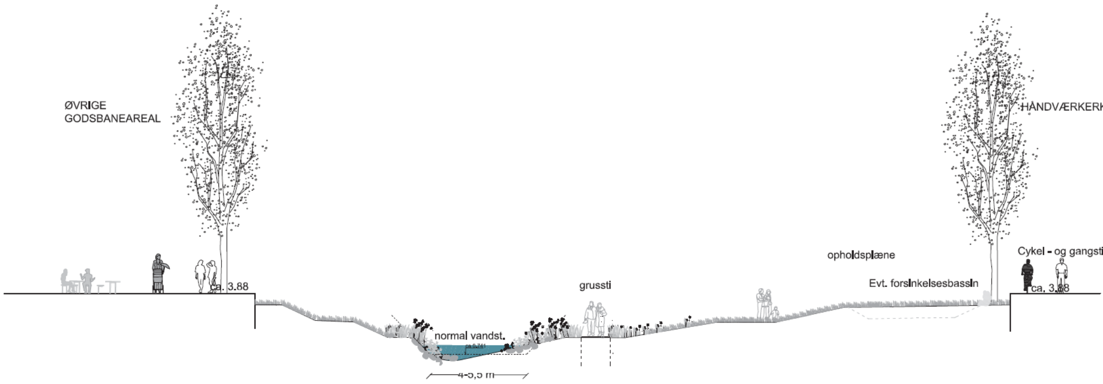

Figure 6.2: Østerå architecture plan mad by Polyform. [Arkitekter, 2015]

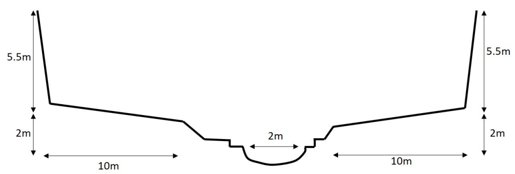

Figure 6.3: Øster cross section in the current path.

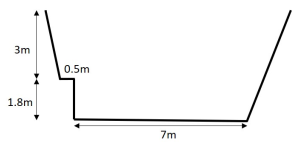

Figure 6.4: Øster cross section in the down stream (Before the basin in figure 5.1).

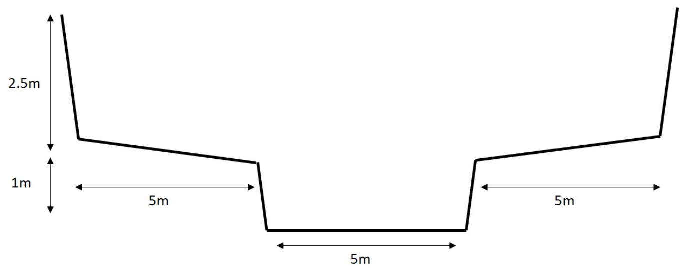

Figure 6.5: The selected dimension for Østerå new path.

The new path setup consists of 3 catchments covering an area of 6ha. with 23 manholes and 22 pipes. The new stream set up is shown in figure 6.6.

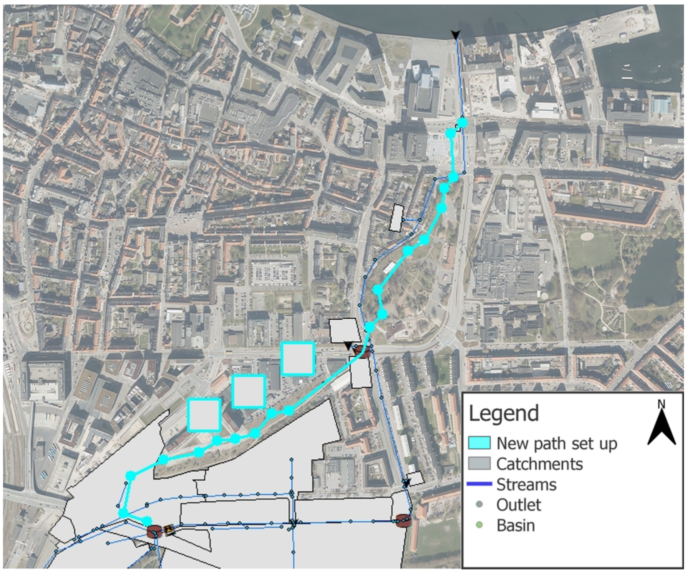

Figure 6.6: The new path set up in Mike Urban.

The opening of the Østerå new path is one of several changes in the area, the objective of which is to build several structures to increase the attractiveness of the urban area, the stormwater from these structures is expected to contribute directly to the stream that is why the northern part of the district must be taken into account. Therefore a three new catchment of 2 ha has been placed in the model as can be noticed above. Imperviousness of 70 % is assumed for the new catchments, where the hydrological reduction factor defines the percentage of the impervious area contributing to the surface flow towards the sewer. Since the hydrological processes during a rainfall are difficult to determine, an assumption based on literature values is used. Where the recommended value for residential catchments is between 0.7–0.9.

An average Manning Roughness of 50 $\frac{m^{1/3}}{s}$ is assumed for the new path in order to represents the roughness or friction applied to the flow in the channel and it depends on the materials type and in many flow conditions the selection of a manning's roughness coefficient can greatly affect the model efficiency. The manning number of the existence material in Mike model is used to predict the degree of roughness in channels as can be seen in table 6.1.

Table 6.1: The Manning Roughness (M_R) in Mike Urban Model.

Parameter	Unit	Value
Average Manning Roughness in the current path	$\frac{m^{1/3}}{s}$	55
Average Manning Roughness in the down stream	$\frac{m^{1/3}}{s}$	50
Average Manning Roughness for the new path	$\frac{m^{1/3}}{s}$	50

6.3 1D-2D Overland Simulation

The overall objective of this project is to evaluate the consequences of the new channel and to produce flood risk maps showing a likelihood of flooding. This can be done by using Mike flood model, where the historical rainfall data set together with a coupled 1D/2D surface and network model allows to analyze and assess the potential flood where recently this model has become a standard to use in Denmark. Therefore, the overland flow modelling in this project is carried out with MIKE Flood. Mike flood is 1D runoff model (pipe flow and river) + 2D surface model, where the runoff from the catchments goes to the network system before it goes up again through the coupled manholes. This transportation is performed in Mike by using the shallow water equations. The hydrodynamical surface flow model is able to solve the shallow water equations in a structured grid by using a digital elevation model (DEM).[DHI, 2017a]. Shallow water equations is based on the three-dimensional incompressible Reynolds averaged Navier-stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure. The local continuity equation and the two horizontal momentum equations can be seen in equations 6.3, 6.4 and 6.5.[DHI, 2017b]

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S \tag{6.3}$$

$$F_u=\frac{\partial}{\partial x}(2A_v\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(A_v(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})) \tag{6.4}$$

$$F_v=\frac{\partial}{\partial y}(2A_v\frac{\partial v}{\partial y})+\frac{\partial}{\partial x}(A_v(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})) \tag{6.5}$$

Where:	F_u *and* F_v	the horizontal stress	[kg.m^{-1}.s^{-2}]
	x,y *and* z	The Cartesian coordinates	[m]
	u,v *and* w	The velocity components in x,y and z direction	[m/s]
	S	The storage	[m^3/s]
	A_v	Horizontal eddy viscosity	[m^2/s]

6.4 Flood Risk Assessments

To assess the flood in the case study and indicate the difference before and after the implementation of the new path of Østerå, two scenarios are selected to be simulated in the Flood Model. Where these two situations are described as follows:

- Current Scenario : The situation before the implementation of the new channel of Østerå. In this scenario the water flows from the weir as illustrated in figure 5.1 and figure 3.1 through the current path in Sønderbro and runs through Karolinelund before it ends up to the limfjord.
- New Scenario: The situation after the implementation the new path of Østerå in Godsbanearealet district as described in figure 5.1 and figure 3.1. In this scenario the whole flow will be exchanged to the new path in Godsbanearealet and then continues in the new path in Karolinelund before it ends up also in limfjord.

In both simulations all the flow is directed to the new path or to the current path. In regard to the grid size in Mike Model, a grid with resolution of 5x5 m^2 is chosen. The choice of the grid size has made based on a sensitivity analysis of the grid size in Mike Model and the result is shown in Appendix B.

6.4.1 Current Scenario Result

Every rain event in table 5.1 is tested by Mike Flood Model in order to evaluate the likelihood of flooding in the project area. Where a full 1D/2D simulation of the 13 selected rainfall events has been performed and its results analyzed with special focus on the observed flood area and maximum flood depth as can be seen in table 6.2. The result of these simulations shows a difference between the return period based on the accumulated value presented in table 5.1 and the return period based on the flooded area. The difference between the return period based on flooded area and accumulated value as can be seen in figure 6.7 is due to the difference between the rain duration and the intensity of rain events specially the duration and the severity of the peak which cause the flood. Therefore the selection of the rain events ensures the variability of rainfall types, from extremely high peak storms with a short duration to a more moderate rainfall with longer duration. The average and maximum flood depth is calculated based on the most critical area along the two paths of Østerå in the project area and the result is shown in table 6.2.

Table 6.2: The observed result of the selected rainfall events in the current scenario which performed with Mike flood model.

Event Number	Average flood depth [cm]	Max flood depth [m]	Flooded area [ha]
1	17	1.33	20.62
2	15	0.75	19.37
3	15	0.71	14.92
4	13	0.67	13.38
5	12.5	0.67	15.38
6	12.8	0.64	13.58
7	12.2	0.69	13.78
8	11.2	0.69	10.53
9	11.7	0.65	12.58
10	11.7	0.64	11.96
11	11.5	0.69	11.93
12	10	0.68	10.93
13	9.5	0.64	8.74

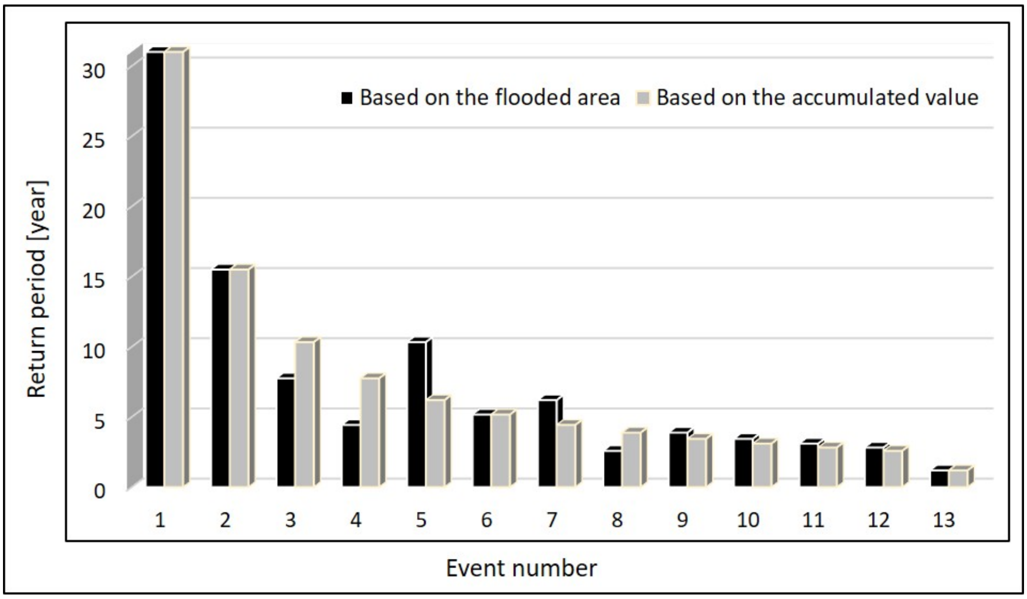

Figure 6.7: The Affected area for each events in the current situation.

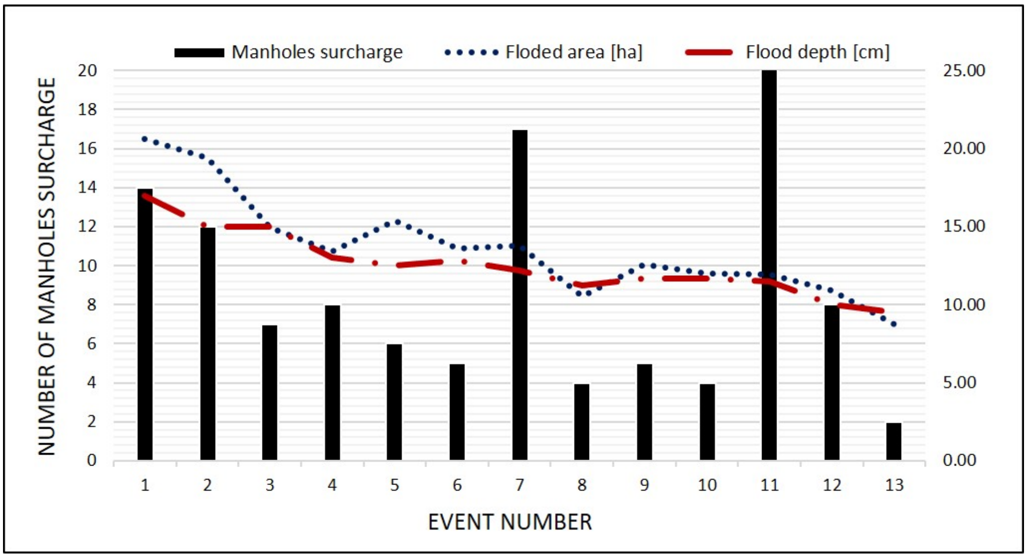

Figure 6.8: The Affected area for each events in the current situation.

Figure 6.8 shows a varying percentage in the number of surcharged manholes in the urban drainage system and there is no clear relationship between the number of surcharged manholes and the observed flood areas or volume. The result of event 1 and event 13 is presented in figure 6.9. These events have been chosen to be presented, since there is a visual differentiation of both criteria the flood depth and affected area. The flood depths below 0.02 m have been neglected and thus floods from > 0.02 are presented. The result of the rest of the rain events is provided in Electronic appendix E.2.

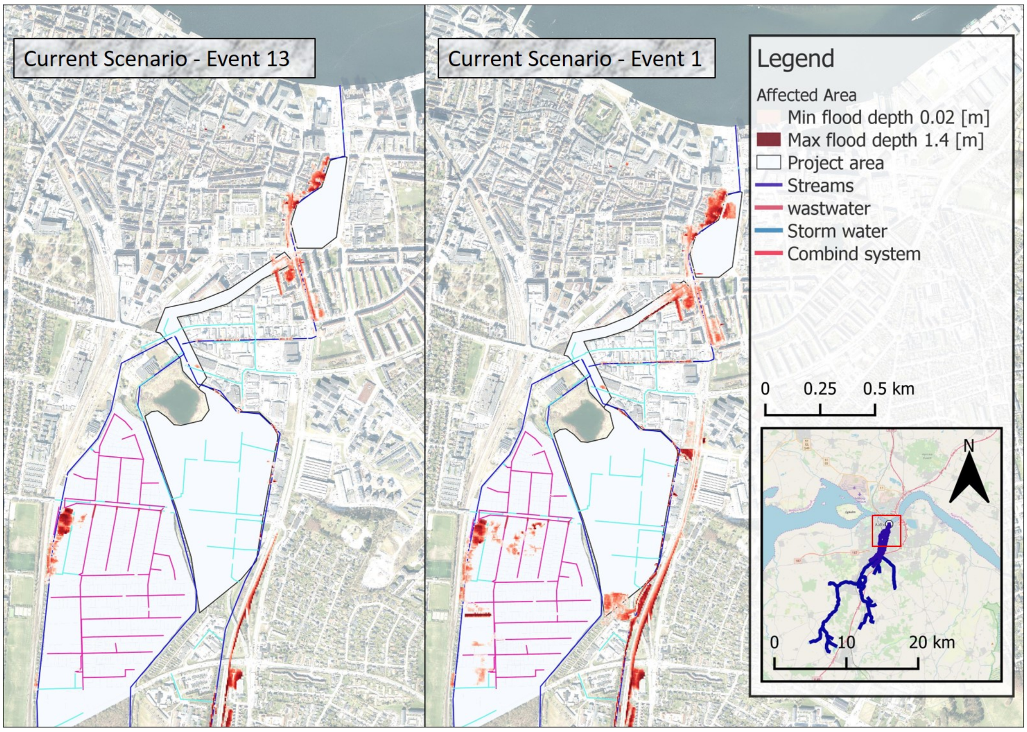

Figure 6.9: The flood prone area in current scenario.

Figure 6.9 shows the area that is exposed to flood risk caused by event 1 in the right side of the figure and event 13 which is on the left side of the figure in the current path scenario. Different flood prone areas can be observed throughout the urban drainage system where both the districts of Kærby and the Karolinelund are a subject to flood. The flood prone areas can be observed in the lower terrain areas in Kærby, where surface water is expected to accumulate. The critical flood in Karolinelund might be the reason behind changing the path to flow through Karolinelund instead of the urban area as illustrated in figure 3.1.

6.4.2 New Path Scenario Result

As already mentioned, every rain event in table 5.1 is tested in Mike Flood Model . The result of the events simulations can be seen in table 6.3 and since the event 1 has the highest return period in regard to the accumulated flow as well as in regard to the flooded area, the rain event number 1 has been chosen to be presented in this study.

The flow in the upstream of Østerå discharge water through the new path in Godsbanearealet district contrary to the previous situation as illustrated in figure 6.10. The variation in the water level in the old path due to the difference discharge are shown in the section A-A in figure 6.11 and 6.12. While the maximum water level in the section B-B of the new channel is shown in figure 6.13. Even though the current channel has no discharge from the upstream flow of Østerå but still section A-A in figure 6.12 in the new path scenario shows some discharge. The water level is due to the runoff from some small catchments connected to the stream and due to the interaction between the drainage system and the limfjord, where the water is a backwater from limfjord therefor the water level in the stream is based on the water level in limfjord.

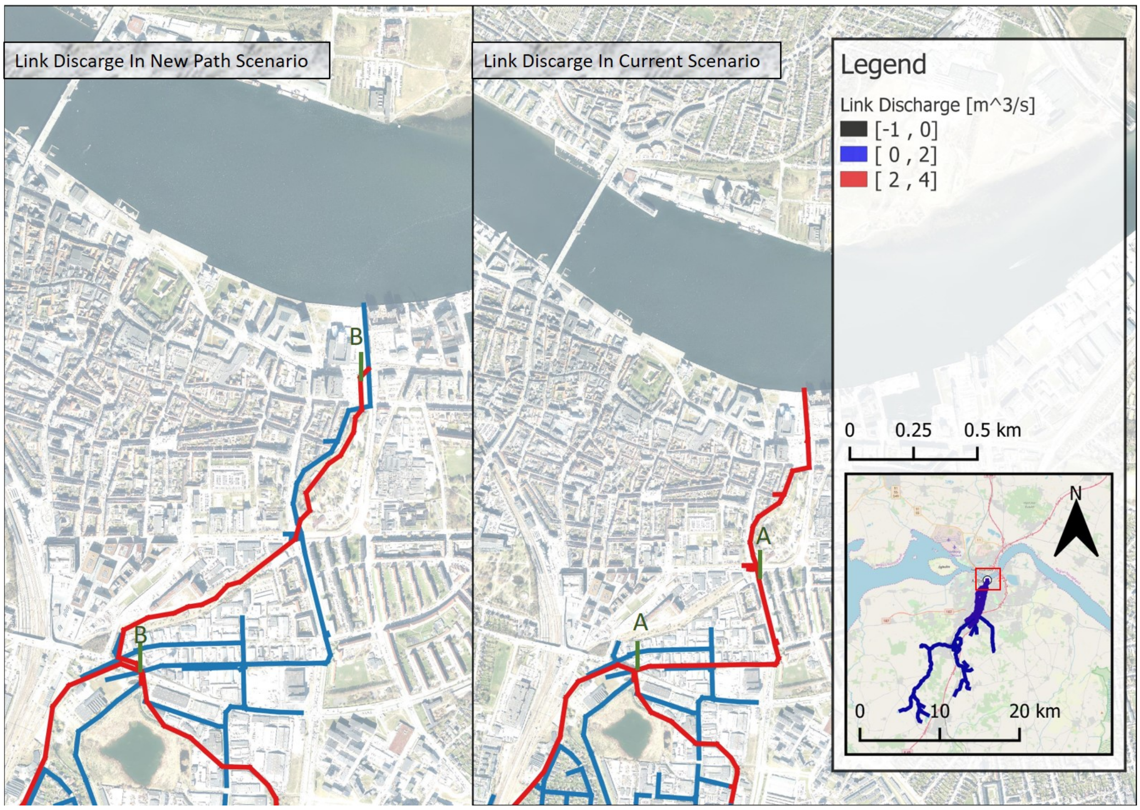

Figure 6.10: The flow discharge in the new and current scenarios, where the flow exchange to the new channel in the new path scenario. NB: Section A-A present the Old path and section B-B present the new path.

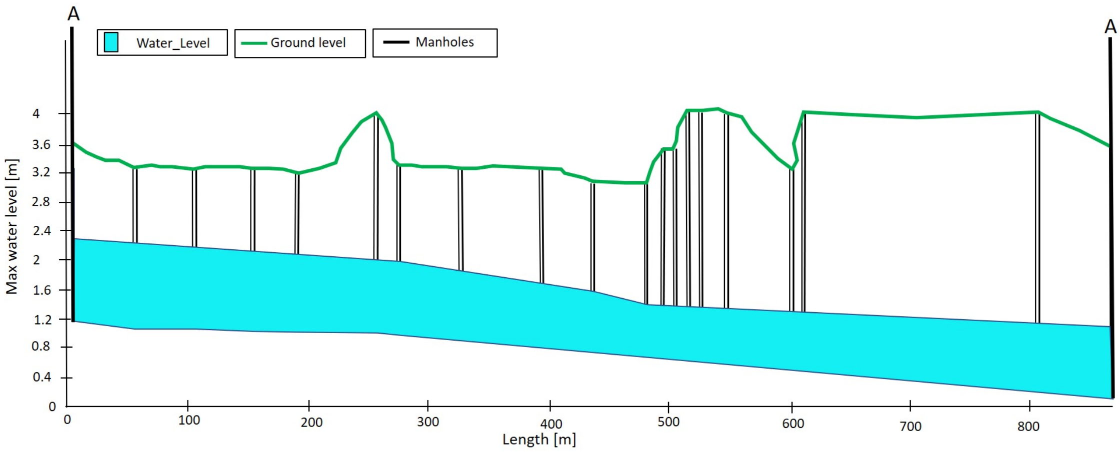

Figure 6.11: Longitudinal section A-A (Section A-A is illustrated in figure 6.10) shows the maximum water level in the old channel in the current scenario.

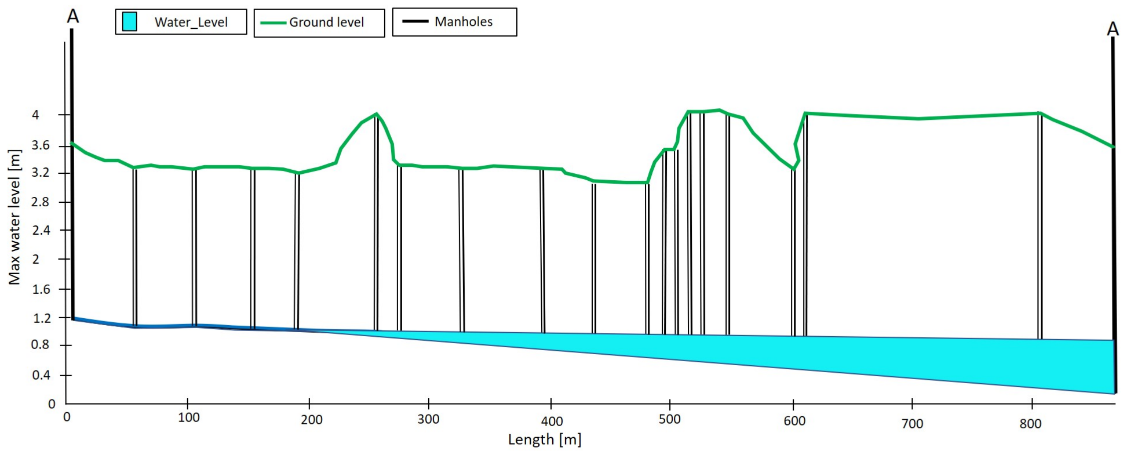

Figure 6.12: Longitudinal section A-A (Section A-A is illustrated in figure 6.10) shows the backwater level from limfjod in the old channel in the new path scenario.

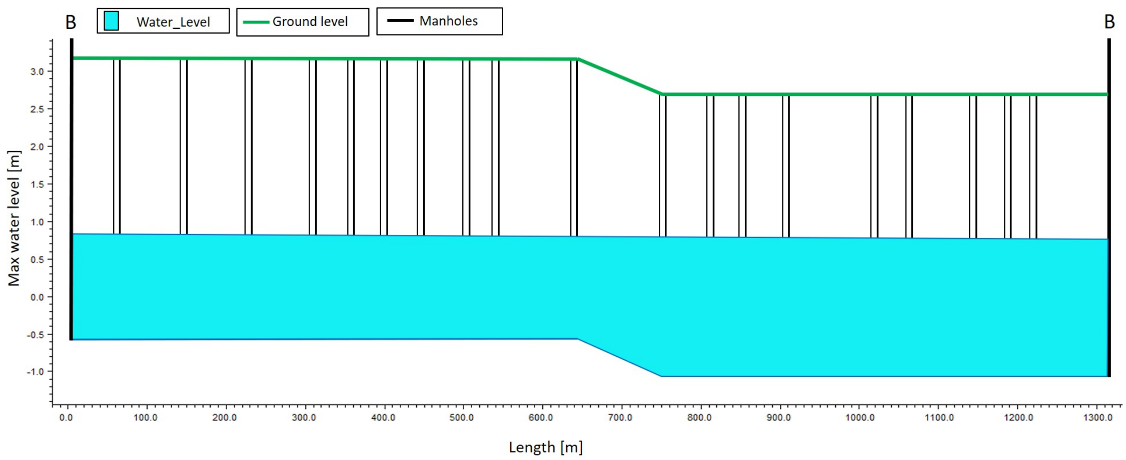

Figure 6.13: Longitudinal section B-B (Section B-B is illustrated in figure 6.10) shows the maximum water level in the new channel in the new path scenario.

Table 6.3: The observed result of the selected rainfall events in the new path scenario which performed with Mike flood model.

Event Number	Average flood depth [cm]	Max flood depth [m]	Flooded area [ha]
1	16.2	1.63	18.42
2	15.9	1.61	16.97
3	15.4	1.58	12.05
4	14.2	1.55	11.05
5	15	1.55	11.41
6	14	1.54	11.07
7	13	1.34	12.05
8	12.5	1.35	9.44
9	13	1.43	9.75
10	12.8	1.34	8.91
11	12	0.64	11.06
12	11.6	0.63	9.67
13	11	0.6	7.24

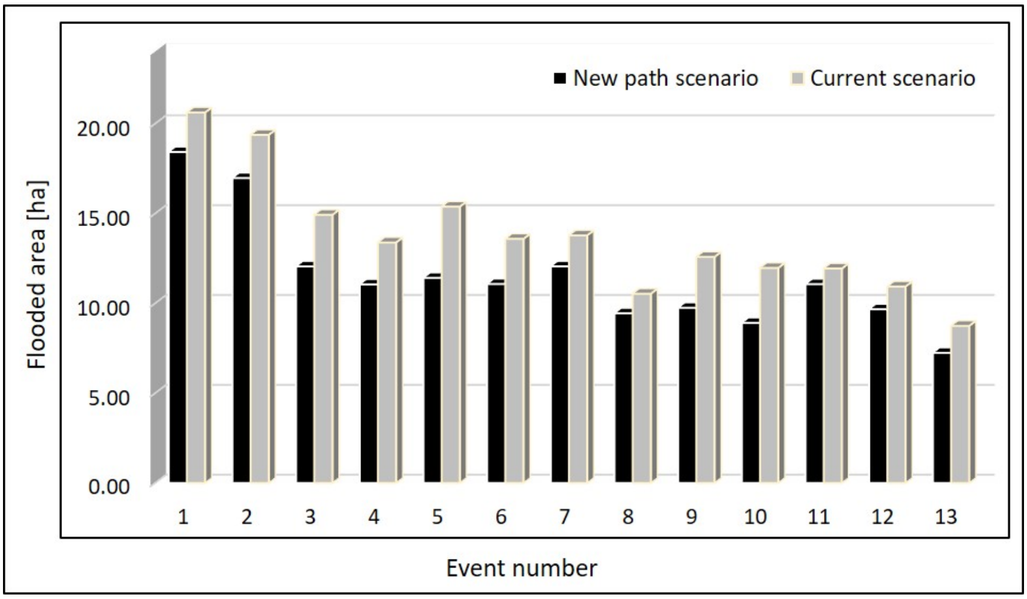

Figure 6.14: Comparing between the new path scenario and the current scenario in regard to the Affected area.

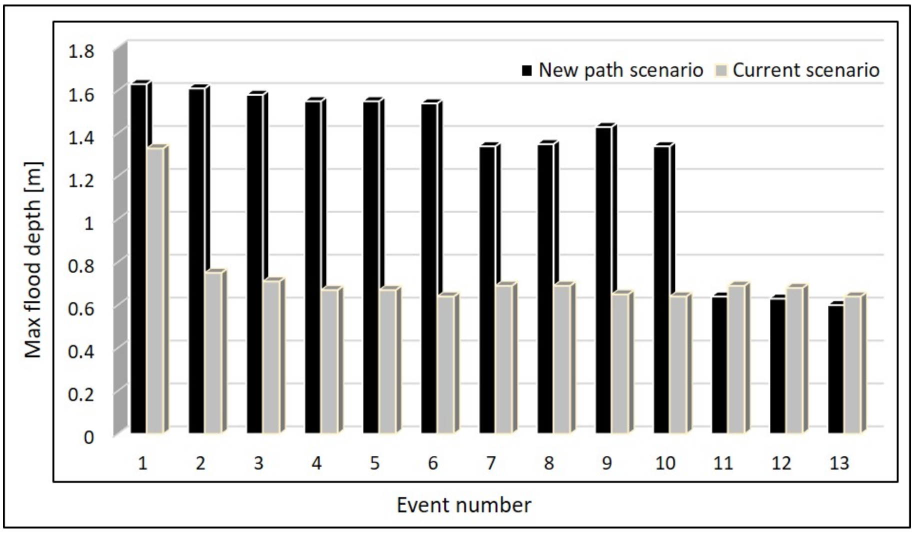

Figure 6.15: Comparison between the new path scenario and the current scenario in regard to the maximum flood depth.

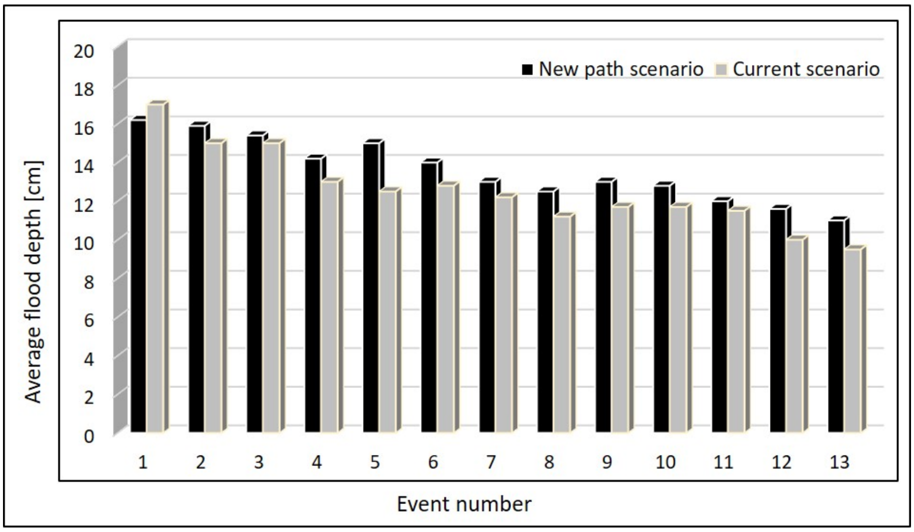

Figure 6.16: Comparison between the new path scenario and the current scenario in regard to the average flood depth.

It can be noticed from figure 6.15 that although the maximum flood depth in the new path scenario is higher compared to the other scenario, but this consider to be limited in a small patch, since the average flood depth in figure 6.16 shows that the values are more identical, and the differences are minimal. As for the flooded area in figure 6.14, the flood prone areas are deceased in the new scenario and such decreasing in the flooded area are more described in figure 6.17

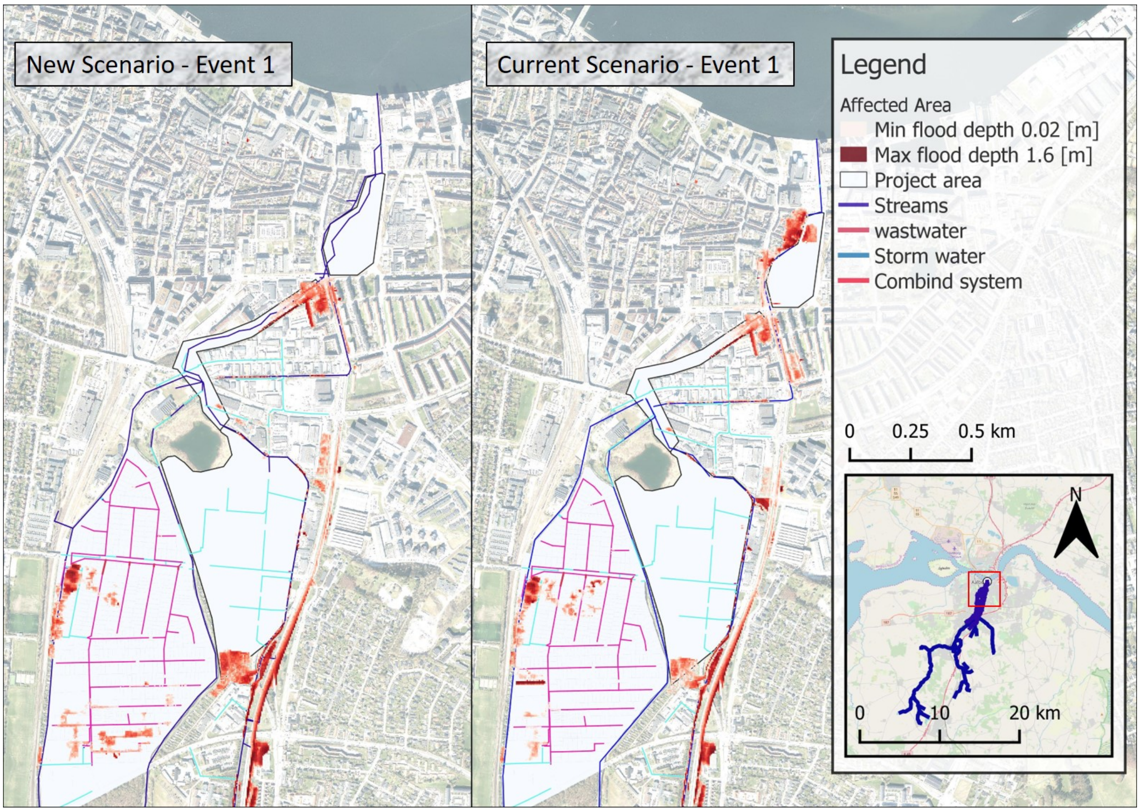

Figure 6.17: Comparing between the flood prone area in the current scenario and in the new path scenario caused by event 1.

The result in figure 6.17 shows a Major changing in the flood prone area in Karolinelund, where the flood prone area is confined to the intersection between Kjellerupsgade and Jyllandsgade Street in 9000 Aalborg. The aforementioned region is currently undergoing maintenance work, including the expansion of the sewage system and reorganization of the current network as can be seen in the appendix in figures D.16 and D.17. This may be dedicated to improve the weaknesses in the drainage system and develop the channel capacity.

On the other hand the flood prone area in Kærby is changed where less flood can be noticed in the northern part of the district of Kærby and more flood to the southern part. To evaluate such a change in the study case an estimation of the flood cost has been made in section 6.5.

6.5 Estimation of Flood Damage Cost

Estimation of the flood damage cost is important in order to evaluate the least harmful scenario. The requirements should be based on either: a cost-benefit analysis (CBA) that describes socioeconomic losses by comparing specific projects or by a socioeconomic optimization, which establishes a service level for stormwater on terrain.[Thorndahl, 2019] Generally the damage model that use to estimation the consequence of the flood is based on two criteria: the land use and the inundation depth. In this project only the land use has been taken into consideration by using an estimation map from [Miljø- og Fødevareministeriet - Miljøstyrelsen, 2013] as can be seen in appendix C.1 where the focus on this map is more on the construction costs and expenses for operation and maintenance. The flood damage to buildings and contents are dependent on several variables as the type of building structure and construction, and the materials of which they are made have a big influence on the nature and extent of damage caused by the flood. The estimation of flood damage cost map is shown in figure 6.18.

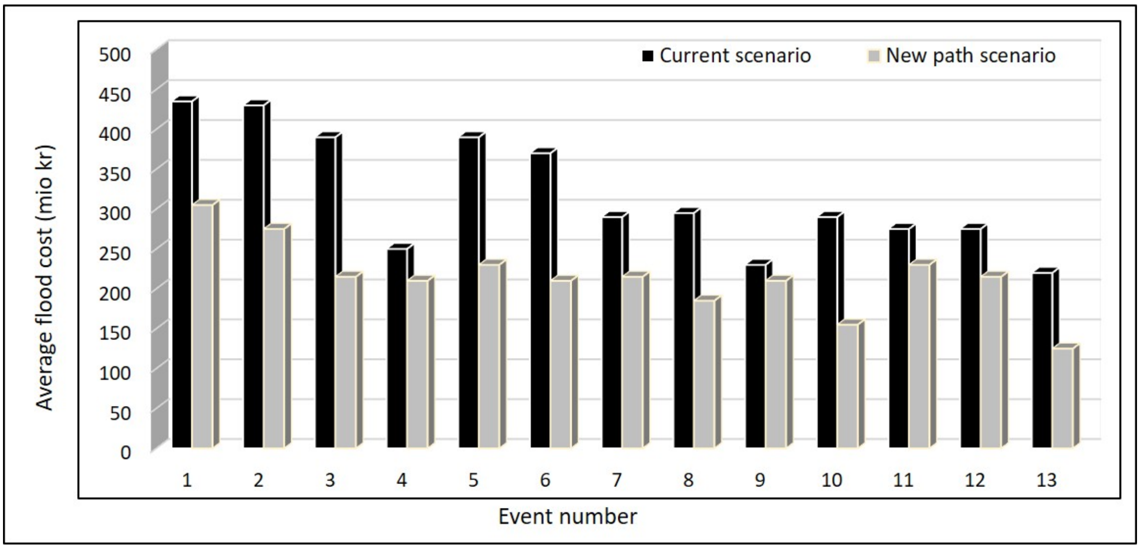

Figure 6.18: The Estimation of the average flood cost based on the building cost in the flood affected area .

It can be noticed that the larger return period in regard to the flooded area and the accumulated value has the highest cost. Based on the result the implementing of the new path of Østerå has a significant impact on the flood cost. This is considered a positive change, especially by avoiding the flooding in the residential area in Karolinelund which is the most expensive area in the project area. A sustainable approach by using a local control is going to be implemented and tested in Mike flood model in the next chapter in order to reuse the current path capacity during the extreme rain event and estimate the new cost of the new approach.

III Solutions and Results

7. Passive and Local Control System

This chapter will contain a brief overview of possibility to provide a sustainable approach by using a passive control and another approach based on the reactive control (local control) in order to minimize the potential flood and optimize the total drainage system.

7.1 Fundamental Concepts and Terms of RTC

This section introduces some of the fundamental concepts and terms of the real time control (RTC). The RTC is a process used to improve the performance of the urban drainage systems. Most of the RTC systems are designed using data processors which execute instructions derived from a software program to accomplish the job for which they were designed, where the objective of using such a system is to utilize the full capacity of the drainage systems. Operational goals have included reducing flooding effects in urban areas and avoiding surcharges in the sewer. The classification of the RTC is based on the control mechanisms [Thorndahl, 2019], these mechanisms can be seen in figure 7.1 and they are categorized as follows :

- Passive control: This type considers the simplest way to implement the RTC where no movable devices regulators are required and the Water is controlled by geometry only.
- Reactive or local control: The local scale is a simple system where the sensor and the flow regulator work together without communication with a control center.
- Global control: The sensors are connected to a control center.
- Integrated or predictive control: Regulators are controlled based on prognosis or forecasters information of the system state.

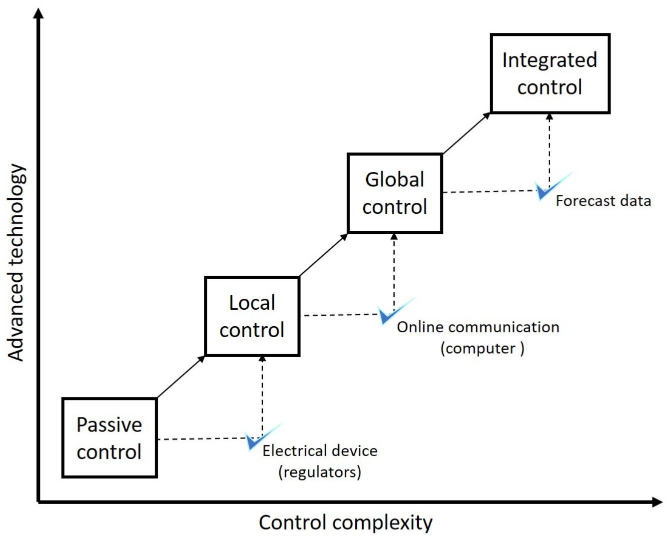

Figure 7.1: Real time control mechanisms [Thorndahl, 2019]

The advanced technology in overall optimization is better but still perceived as complex and difficult operation to implement. Furthermore, the presence of sensors in the foul environment of wastewater systems requires additional equipment for cleaning of the instrumentation. These add to the cost and require extra work to install. Therefore , up today the major part of the urban wastewater systems throughout the world is still operating under static conditions without any form of control nor monitoring of sewer networks. In this project two control scenarios will be implemented in Mike Urban Model. The first scenario is based on a simple passive control and the second one is based on a local control. These scenarios are chosen in order to reluctance of drainage system to complexity, since they have a good performance compared with the overcoming many technological obstacles at reasonable costs.

7.2 The Implementation of the Control Scenarios

As mentioned earlier, the implementation of a sustainable approach is done based on simple mechanisms of RTC, where in Mike Urban, there are many controllable devices that might be used. The device types available are Pump, weir, orifice with gate, Orifice with weir and Valve. Where a weir, orifice with gate and a sensor is used in this project. The overall objective of using the control system is to control the runoff from the residential area in order to decrease the flood prone area as illustrated in figure 7.2

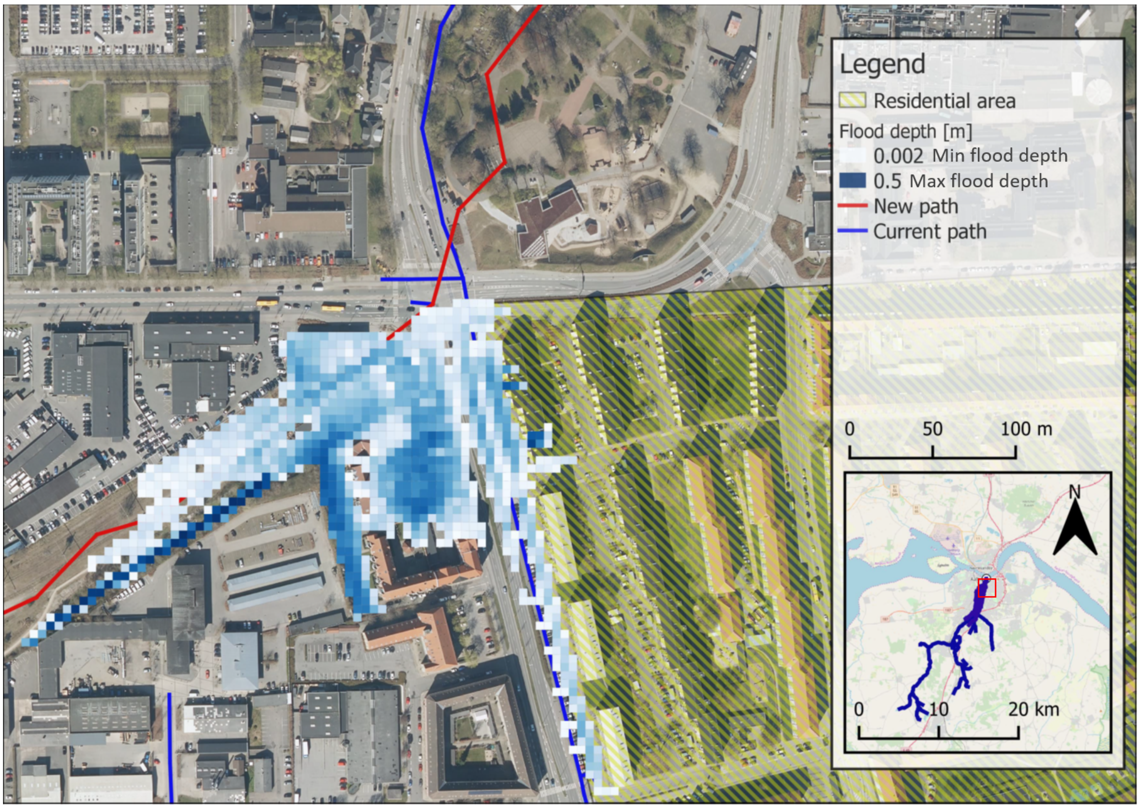

Figure 7.2: Flooding problems in the new path scenario resulting from runoff of a residential area during the rain event number 1.

To handle the flooding caused by the residential area as seen in figure 7.2, two scenarios are tested in Mike Urban Flood Model to evaluate the potential flood in order to optimize the drainage system in the case study. These scenarios are illustrated as follows:

- Passive Control Scenario: The idea in the first scenario is to use the total volume of the current path, where the path in the new path scenario is empty as can be seen in figure 6.12. The aim is to use the capacity of the current path to storage the runoff from the residential area during the rain events as shown in figure 7.3.

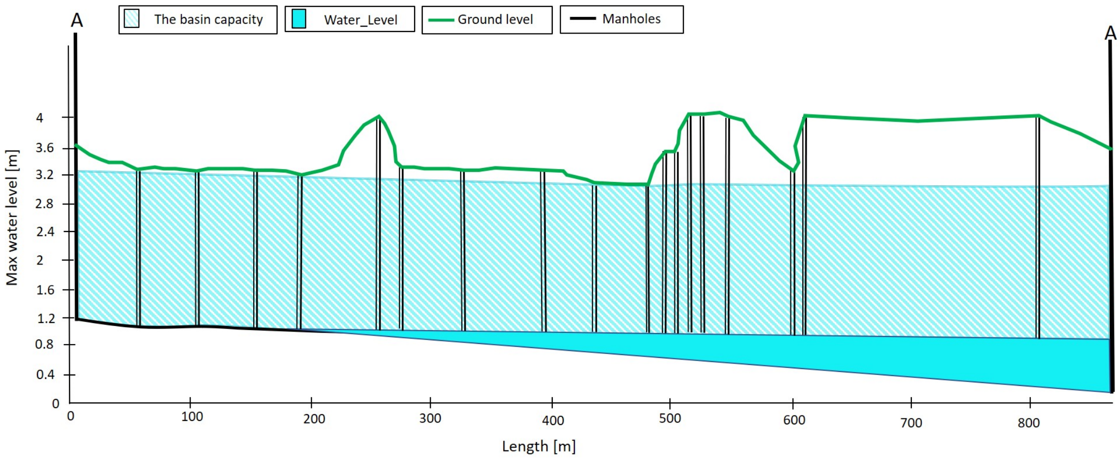

Figure 7.3: Longitudinal section A-A (Section A-A is illustrated in figure 6.10) shows the old channel capacity in order to reuse the current path as a storage basin during the extreme rain events.

Although the capacity of the old channel is based on the water level in limfjord, but this consider to be insignificant due to the huge capacity of the channel that can be used during an extreme rain event compared to the volume of the runoff flow from the catchment. The channel capacity is approximately 38800 m^3 while the runoff from the specific residential area due to rain event number 1 which has the highest accumulated flow is approximately 4000 m^3 and it is 10 times smaller than the current channel capacity.
To achieve the aim of the scenario and in order to close the down stream of the current path during the peak, a simple regulator outlet as a water break, which allows to a certain discharge to flow out of the current basin is required to be installed. A movable weir to store the inflowing stormwater during an extreme rain event, and release it slowly after the peak is gone can also be an option and can be applied. In this project a regulator operating under static conditions by using a passive control is used as it is the most dominated operation all over the drainage system and easy to implement and control. The passive control scenario set up is illustrated in figure 7.4 and the result of first scenario simulation is presented in section 7.3.1.

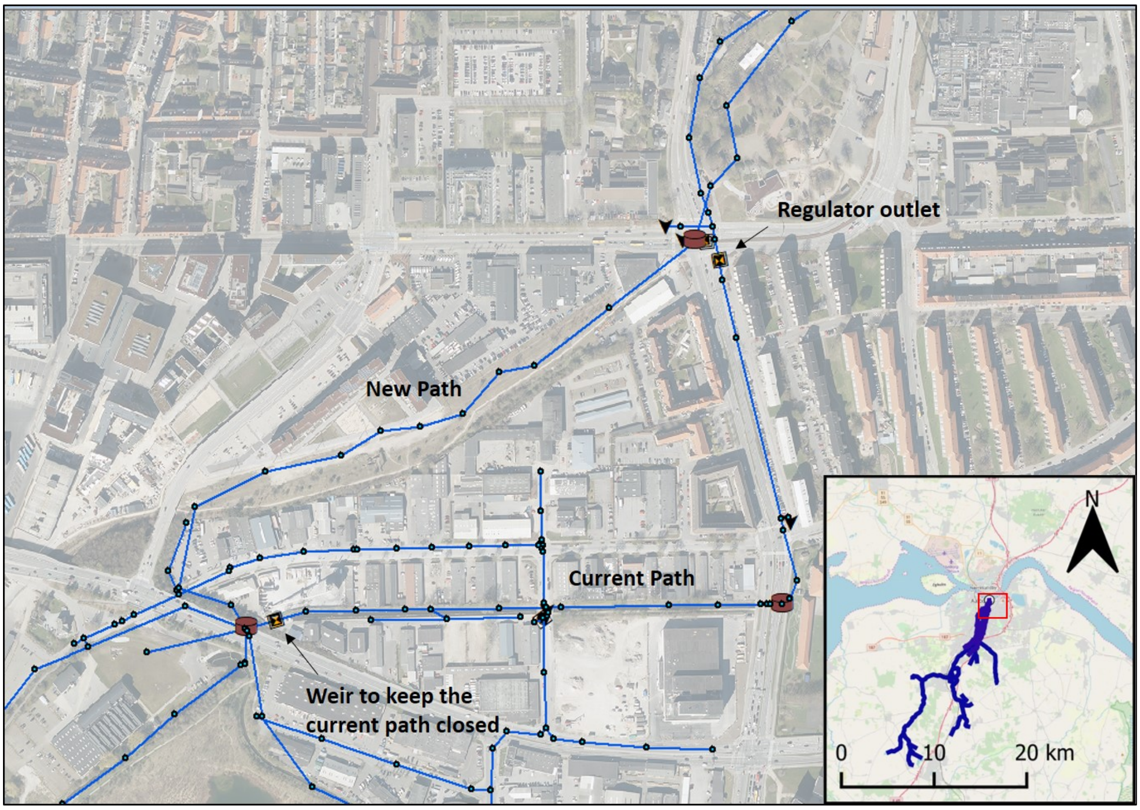

Figure 7.4: The passive control scenario set up. The position of the weir and the regulator outlet.

- Local Control Scenario: The idea in the second scenario is to divide the flow in both paths in the weir point in figure 5.1 by either a passive control weir or a movable weir and implement a new basin in Karolinelund in order to handle the flooding caused by the runoff from the residential area. In all the previous simulations all the flow was directed to the new path or to the current path, while in this scenario the mechanisms of splitting the flow by using a weir into the two paths might be helpful in order to increase the capacity of the new path which serve the objective of the municipality in regard to the separation between the wastewater and the stormwater as mentioned in chapter 1. The main concept of the municipal plan is to decentralize the stormwater discharge and centralize the waste water treatment and such a change lead to increasing in the flow in the streams. Since the municipality has the intention to complete the plan, the idea of driving the stormwater from the residential area through pipes to a small basin in Karolinelund is possible to implement before its discharge to the new path. The basin is located as shown in figure 7.5 and it will serve a dual purpose: a recreation purpose and stormwater control. The intention of a recreational purpose is to use the basin as a basketball court in the dry weather and use it as a stormwater control during the rainfall events. The geometry is based on existing basketball courts which have a volume of 240 m^3 (1x12x20)m.

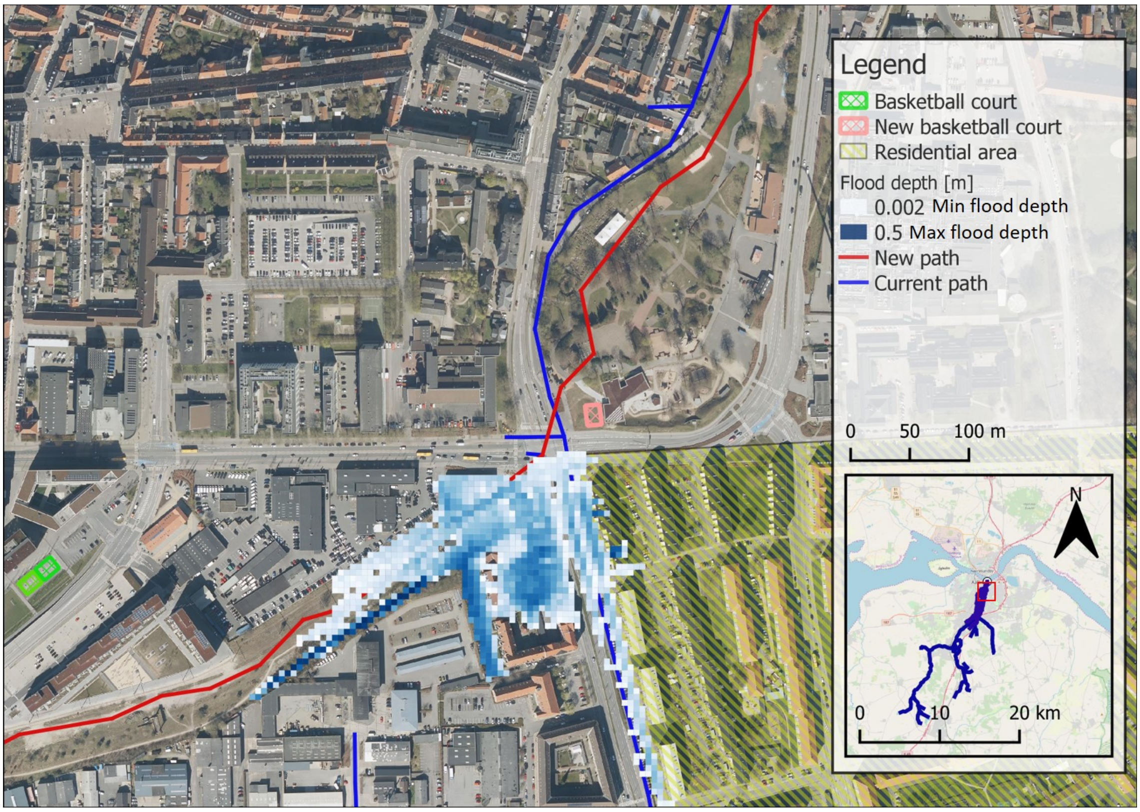

Figure 7.5: Location of the new basin and the existing basketball courts.

To achieve the purpose of the new basin, it must insure that the basin is to be used only during the extreme events and to be neglected during the normal rain events in order to optimize the system and decrease the maintenance procedures cost. This can be done by implementing a sensor which provides information about the actual value of a monitored variable. In Mike Urban the sensor can only monitor one variable. A sensor that capable to measure the water level in the stormwater pipes is implemented in Mike Urban as illustrated in figure 7.6. To determine the movement of the flow into either link A or link B as seen in figure 7.6, a logical condition which demarcates the boundaries of a certain operational situation in the controlled system is used. This frame consists of two of independent logical tests based on the threshold criteria (The water level in the pipe). The logical condition is evaluated as true if the threshold criteria are fulfilled and in this case the gate in link A will still closed and the water will flow into link B before it discharged into the current path . Otherwise, if the logical condition is evaluated as false, then the threshold criteria surpass the limited value and therefore the gate in link A will be opened to allow the water to flow into the new basin and then to be discharged into the new path as seen in figure 7.7. A short analysis to determine the return period of the new path has been made and discussed in chapter 8 section 8.2.2.

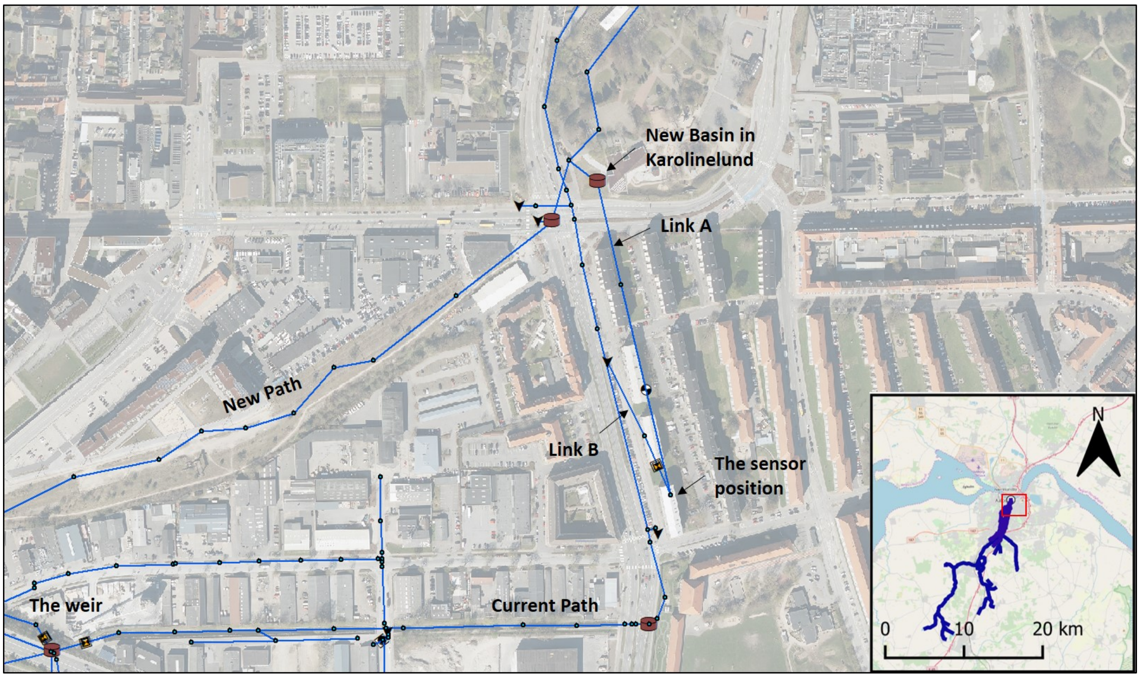

Figure 7.6: The local control scenario set up. The position of the link A, link B and the new basin. The

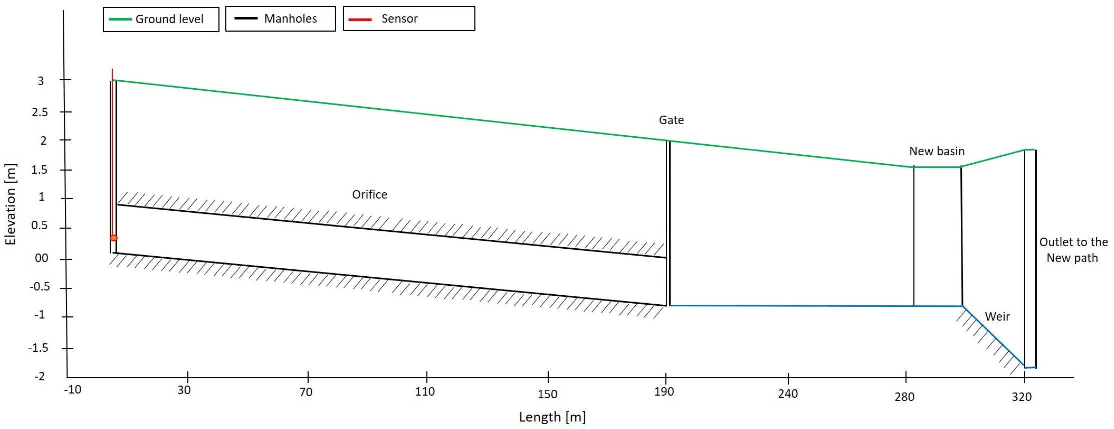

Figure 7.7: Longitudinal section of link A (Link A is illustrated in figure 7.6).

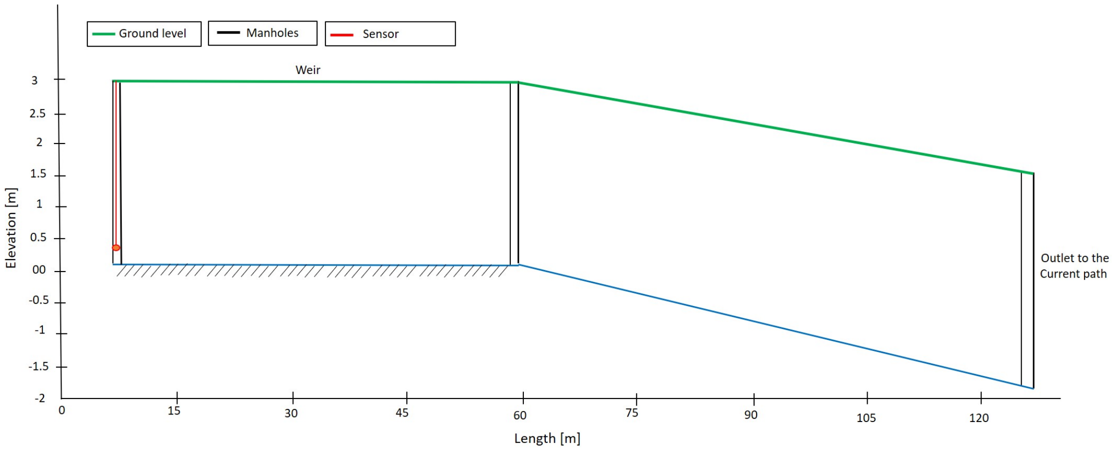

Figure 7.8: Longitudinal section of link B (Link B is illustrated in figure 7.6).

The result of the second scenario simulation is presented in the next section 7.3.2.

7.3 The Control Scenarios Result

Both first and second scenarios are tested in Mike Flood Model in order to evaluate the likelihood of flooding in the project area and the effect of implementing those scenarios on the case study . As mentioned earlier, since the event 1 has the highest return period in regard to the accumulated flow as well as in regard to the flooded area, the rain event number 1 is chosen to be presented in this section as well.

7.3.1 Passive Control Scenario Result

The result of implementing the first scenario shows that using the old channel as a storage basin is sufficiently capable of Containmening the runoff from the catchment and reducing the extent of the flood, where the flood depth decreases and the flooded area decreased by 15 % as can be seen in figure 7.10 and the new cost of such decreasing is shown in figure 7.18. In regard to the water level in the streams, the water level in section A-A increased as shown in figure 7.15. The water level in the current path raised due to the storage volume, where the water volume increased by approximately 7560 m^3. Such a change might have a negative impact in the future due to the climate change, therefore the first scenario must be tested on the future condition as well. The result of projecting the future condition can be seen in chapter 8. The discharge in the old and new path in the up stream weir is shown in figure 7.9

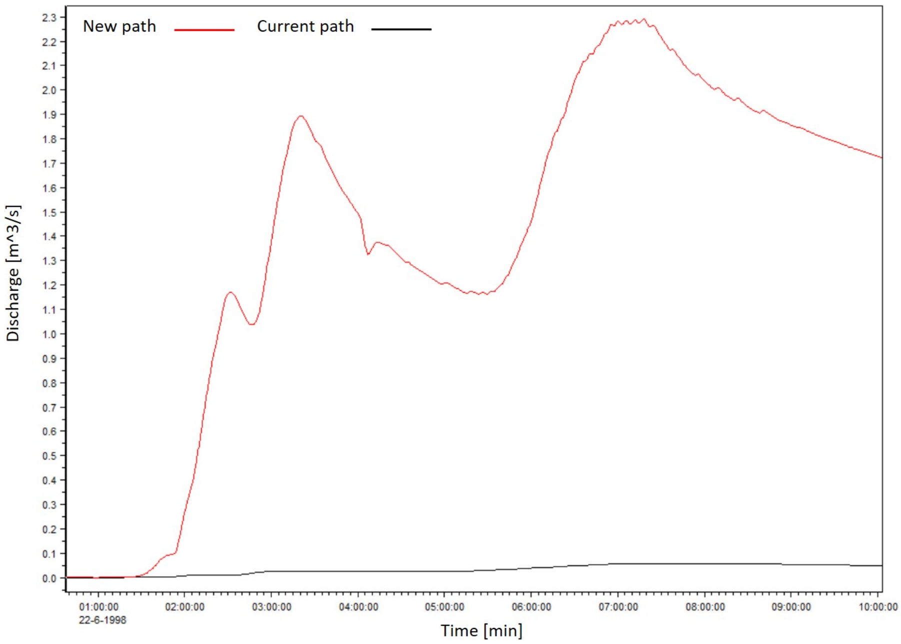

Figure 7.9: The discharge for old and new path in the up stream weir in the first scenario (The weir position is illustrated in figure 7.6) caused by event 1.

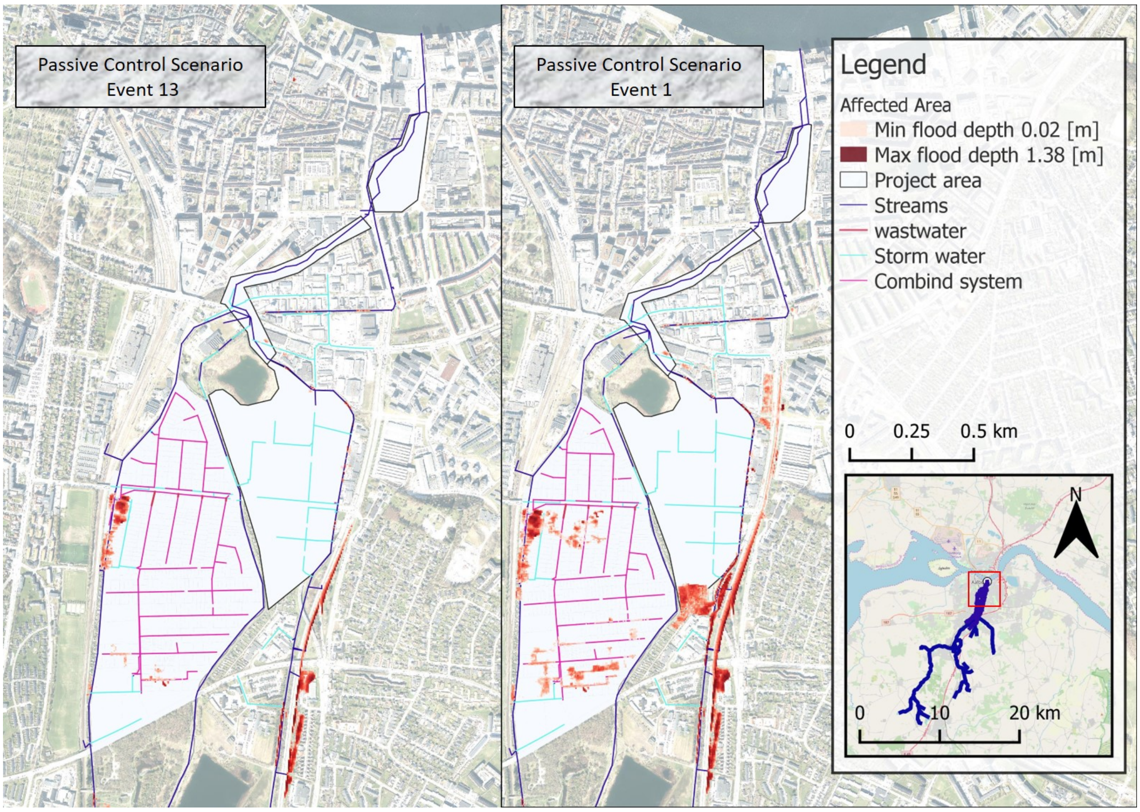

Figure 7.10: The flood prone area after the implementation of the first senario.

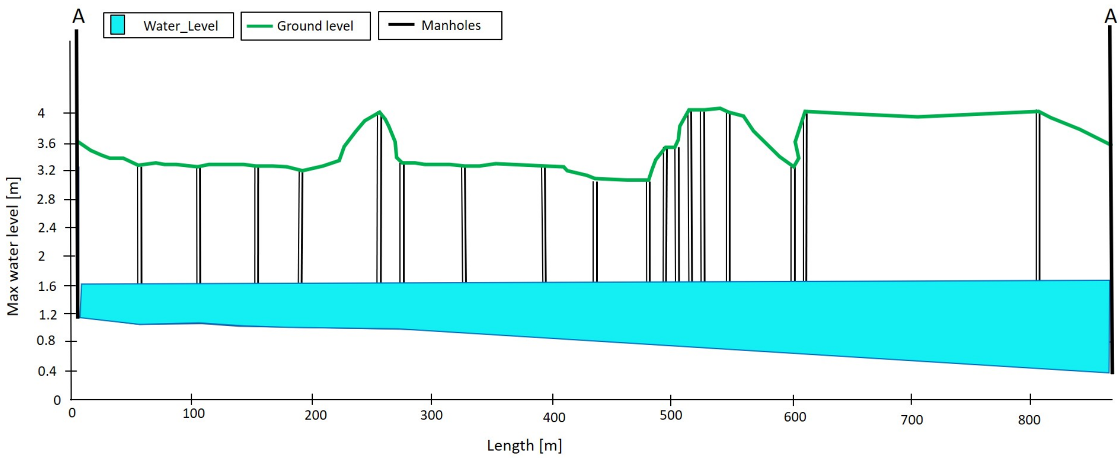

Figure 7.11: Longitudinal section A-A (Section A-A is illustrated in figure 6.10) shows the maximum water level in the old channel in the first scenario.

7.3.2 Local Control Scenario Result

In regard to the flood depth and flooded area, the second scenario shows similar sufficiency of reducing the extent of the flood in the study case. However, the result of using the second scenario shows insignificant effect on the water level in the section A-A and section B-B. dividing the flow in two paths as shown in figure7.12 might not be that important for the new path since the new path is more affected by the water level in the limfjord. That is why the changes is not very visually significant in figure 7.15. The interaction between the drainage system and the limfjord has the biggest impact on the water level in the new path, where the geometry of the new path has major rules appoint that. The current path cross section is shown in figure 7.14.

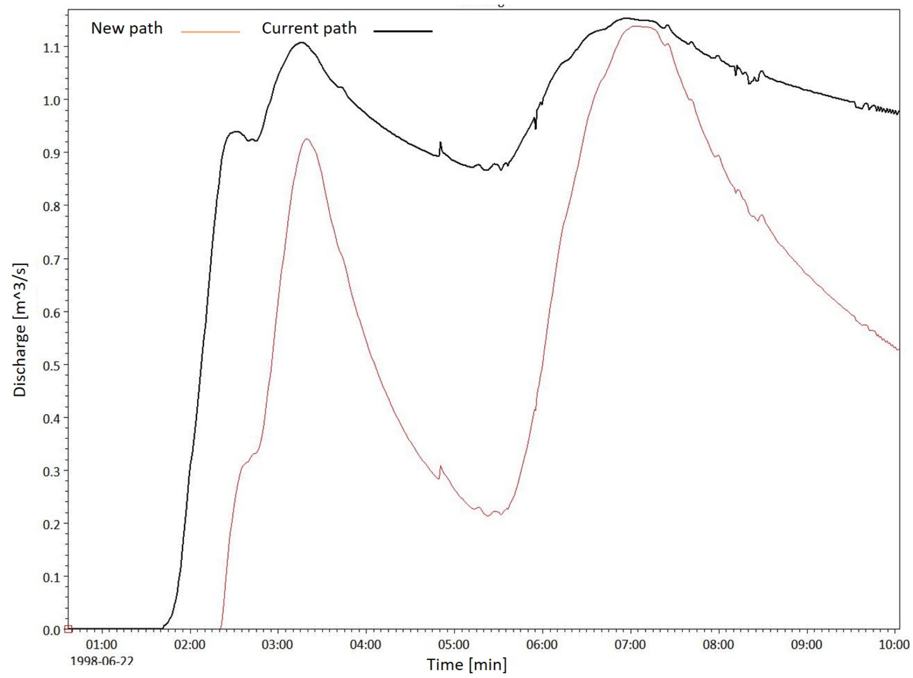

Figure 7.12: The discharge for old and new path after dividing the flow by using the local control in the weir in the second scenario (The weir position is illustrated in figure 7.6) caused by event 1.

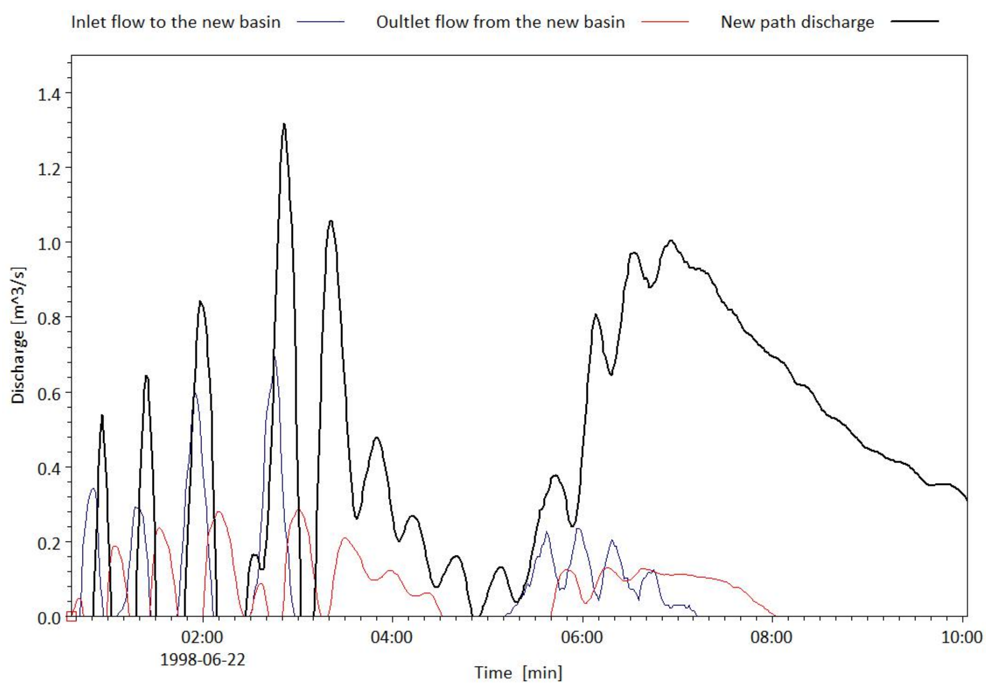

Figure 7.13: The discharge in the new path comparing to the inlet and the outlet discharge in the new basin in the local control scenario caused by event 1.

Figure 7.12 and 7.13 show that the new basin is an effective tool to decrease and to delay the runoff peak in order to separate the runoff peak from the stream peak and to avoid the weaknesses in the drainage system.

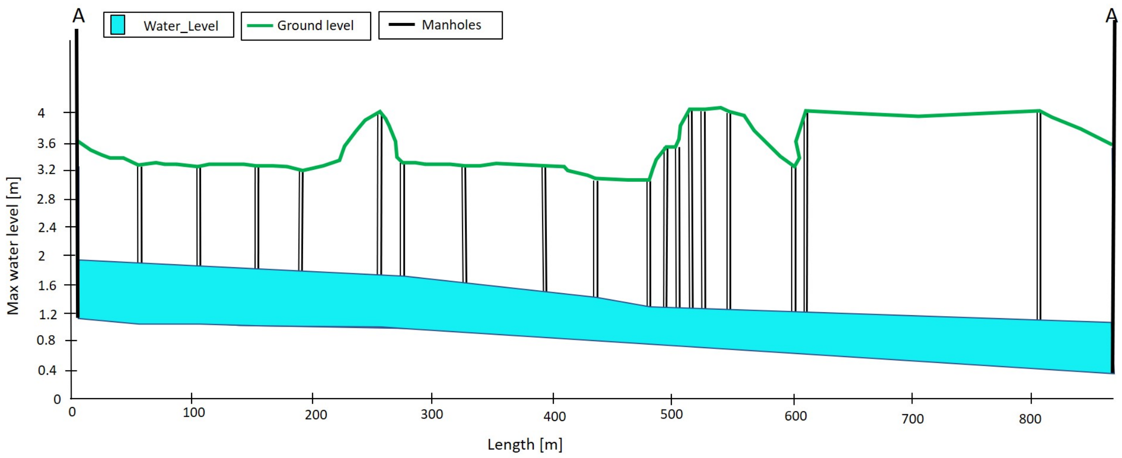

Figure 7.14: Longitudinal section A-A (Section A-A is illustrated in figure 6.10) shows the maximum water level in the old channel in the second scenario.

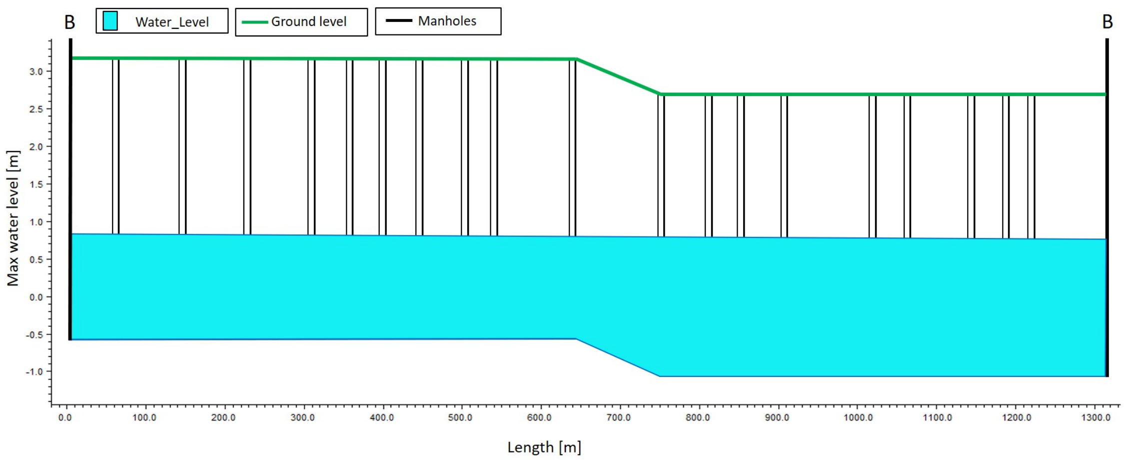

Figure 7.15: Longitudinal section B-B (Section B-B is illustrated in figure 6.10) shows the maximum water level in the new channel in the second scenario.

The second scenario also tested on the future condition and the result of projecting the future condition can be seen in chapter 8.

Despite the cost of implementing a new basin in the second scenario and the difficulty of driving the runoff into the basin, still the second scenario considers a satisfactory result in order to decrease the flood cost. Both the control scenarios show a decreasing in the cost of the flooded area as shown in figure 7.18. The flood area and flood volume is shown in figures 7.16 and 7.17.

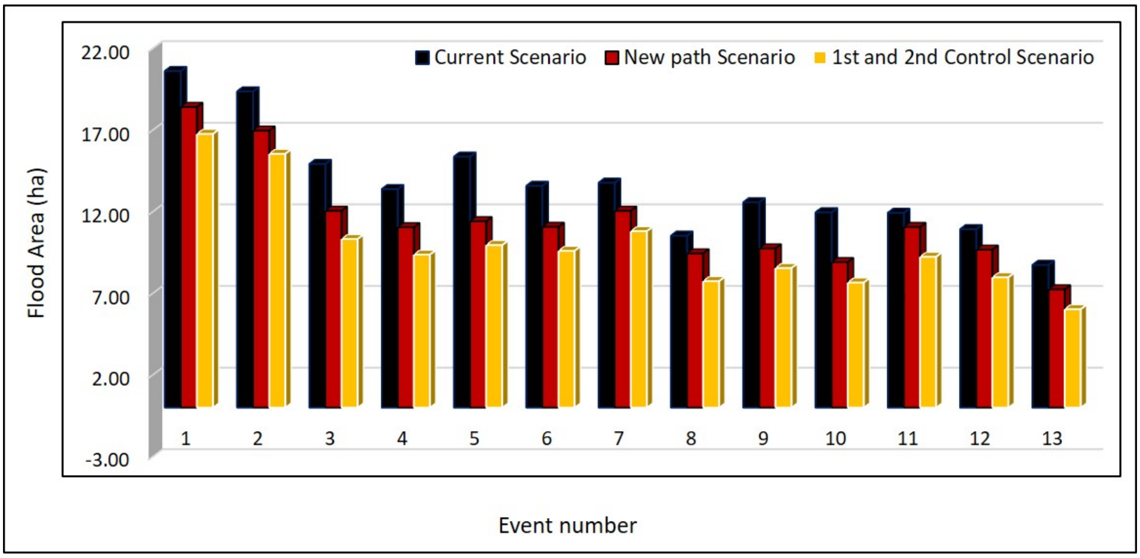

Figure 7.16: The flooded area obtained after the simulation of the selected rainfall events.

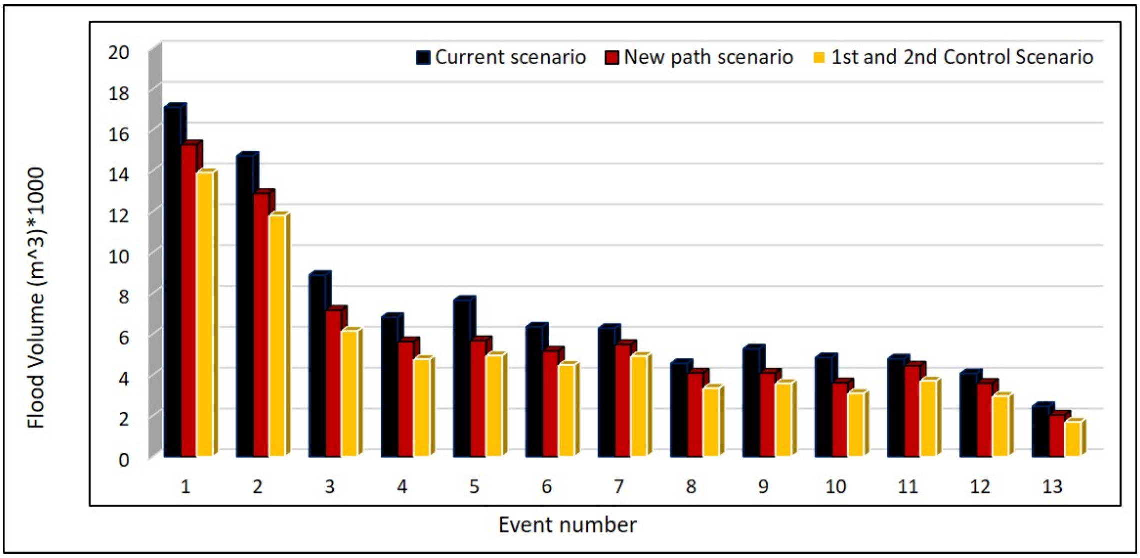

Figure 7.17: The flood volume obtained after the simulation of the selected rainfall events.

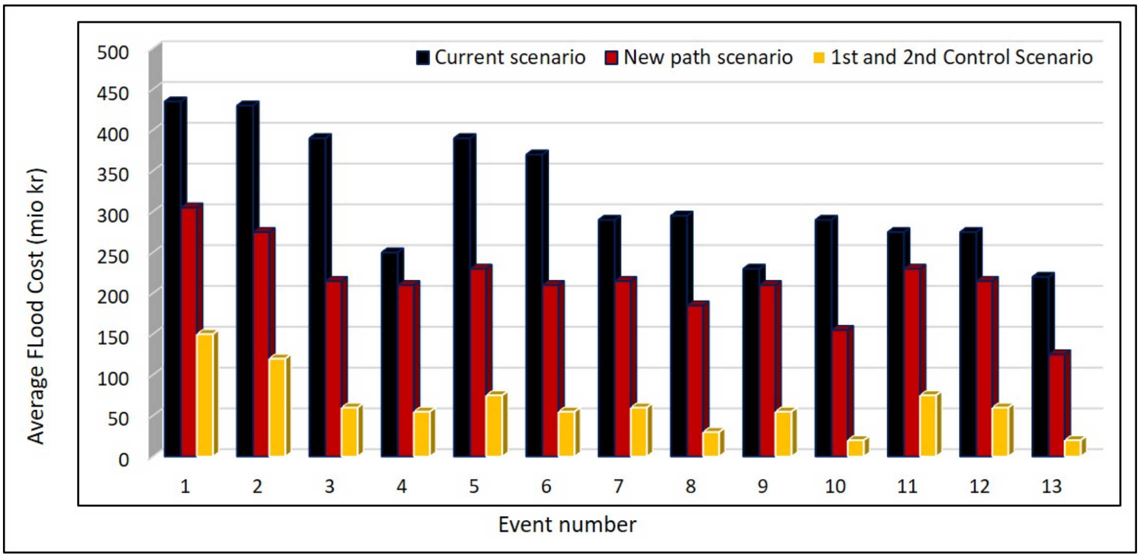

Figure 7.18: The Estimation of the average flood cost based on the building cost in the flood affected area.

The sharp decrease in the average cost is due to the improvement made in the Karolinelund district after the implementation of the passive and local control ,which is considered the most expensive area in this project. This result shows the high performance of the RTC in order to decrease the concerning the risk of flooding .

8. Climate Change Impacts on the Project Area

This chapter provides a review of the current state methods for assessing the impacts of climate change on precipitation at the urban catchment scale and how to apply a climate projected rain series.

8.1 Introduction and Definitions

Until recently, there has been a strong evidence that due to the global warming the probabilities and risks of sewer surcharge and flooding are changing. Therefore, flood risk management plans must be taken into account, with a view to avoiding and reducing the adverse impacts of the floods. According to European Parliament on 23 October 2007 on the assessment and management of flood risks, it is recommended that the European States should provide and prepare a flood risk management plan for prevention, protection and preparedness with a possibility for maintenance and restoration plan in order to reduce the damage to human health, the environment, cultural heritage and economic activity. Where the European floods directive recommends the European member states to prepare a flood risk assessment and flood risk maps showing a likelihood of flooding. The preparation of flood hazard maps and flood risk maps should show a flood corresponding to return period $\geq$ 100 years.[THE EUROPEAN PARLIAMENT, 2007]

According to the WPC of IDA in publication n.27 [Ingeniørforeningen i Danmark-IDA, 2005], there are three different methods to design the drainage system based on the complexity of the drainage system. In calculation level 1 (Small Drainage Systems) and calculation level 2 (Simple Drainage Systems), the urban drainage systems are designed with intensity–duration–frequency (IDF) or types of design storms such like CDS. Where basically, both methods assume agreement between the return period of the rain intensity and the return period of the critical load in the drainage system. The climate projection of these types can be relatively simple by multiplying the design rain by a bias climate factor as illustrated in table 8.1.

Table 8.1: Recommended climate factors for design of drainage systems in Denmark according to WPC of IDA n.30 for the period of 2017-2100 [Gregersen et al., 2014].[Søren Thorndahl1 and Larsen2, 2017]

Return period (years)	Climate factors for the period 2071–2100		
	Scenario A2 (WPC, 2008)	Scenario RCP4.5 (WPC, 2014)	Scenario RCP8.5 (WPC, 2014)
2	1.20 (±0.1)	1.20 (±0.1)	1.45 (±0.1)
10	1.30 (±0.2)	1.30 (±0.2)	1.70 (±0.2)
100	1.40 (±0.3)	1.40 (±0.3)	2.00 (±0.3)

As mentioned earlier the multiplication of climate factors assumption to design storms IDF relationships, is sufficient and can only apply for calculation level 1 and 2. However, for more complex drainage systems with nonlinear rainfall runoff response the simple design methods are not valid for calculation level 3 (Complex Drainage Systems). In complex system the return periods of the rainfall intensity are not in agreement with the return periods of the corresponding drainage system state. Therefore, resampling the historical rainfall series are required in order to estimate the future climate. The idea of resampling the historical rainfall series are to use different climate variables as target variables in order to statistically represent both extremes as well as yearly and seasonal precipitation as can be seen in table 8.2.

Table 8.2: The Danish climate changes in annual and seasonal precipitation as well as extremes.[Søren Thorndahl1 and Larsen2, 2017]

Parameter	Climate factors for the period 2071–2100		
	Scenario A1B (Olesen et al., 2014)	Scenario RCP4.5 (unpublished)	Scenario RCP8.5 (unpublished)
Annual precipitation	1.14 (±0.06)	1.08 (±0.06)	1.14 (±0.07)
Winter precipitation (DJF)	1.25 (±0.06)	1.12 (±0.06)	1.24 (±0.07)
Spring precipitation (MAM)	1.13 (±0.06)	1.13 (±0.08)	1.23 (±0.11)
Summer precipitation (JJA)	1.05 (±0.08)	1.06 (±0.18)	1.03 (±0.21)
Fall precipitation (SON)	1.13 (±0.06)	1.05(±0.07)	1.09 (±0.13)
Events above 10mm	1.37 (±0.12)	1.20 (±0.13)	1.35 (±0.14)
Events above 20mm	2.50 (±0.14)	1.41 (±0.30)	1.80 (±0.40)
Max. daily precipitation	1.16 (±0.12)	1.12 (±0.09)	1.24 (±0.11)

Since the project focuses on a few selected rainfall events and the simulations run on a specific single rain event, a simplification of the projecting of the climate factor is intended to promote the understanding of a more complex system. The simplification is made based on the exclusion of some details by neglecting the seasonal variation and using the multiplication of climate factors assumption to avoid the complexity. Where the recommended climate factor values in table 8.1 for the design of drainage systems in Denmark according to WPC is used to determine the climate factor. Regarding to the representative concentration pathways Scenarios, a Scenario RCP4.5 that corresponds to an increase in radiation exposure to 4.5 W/m^2 is selected. And since the drainage system in Aalborg municipality is designed for a return period of 10 years for surcharging the ground level, a climate factor of 1.3 is chosen.

In regard to the boundary condition, the water level in the streams and in Limfjord will be affected also by the climate change. According to a study made by the DHI the water level in Limfjord will rises by 15 to 60 cm due to the climate change.[Christensen, 2015]

Despite the selected rain events will increase by 30%, but the total precipitation for the period of 2100 will not have the same increasing factor. It is expected to have more extreme events in the future but with longer time between the events, That is why the stream require a different climate factor. As it can be seen in table 8.2, the Danish climate change in annual precipitation for Scenario RCP4.5 is 1.08 for the period of 2100 which is used in this project for the streams.

8.2 The Result

Both the passive control scenario and the local control scenarios are tested in the future condition in Mike Flood Model in order to evaluate the consequences of the climate change for the period of 2100. The impacts of climate change on the yearly return period is shown in figure 8.1

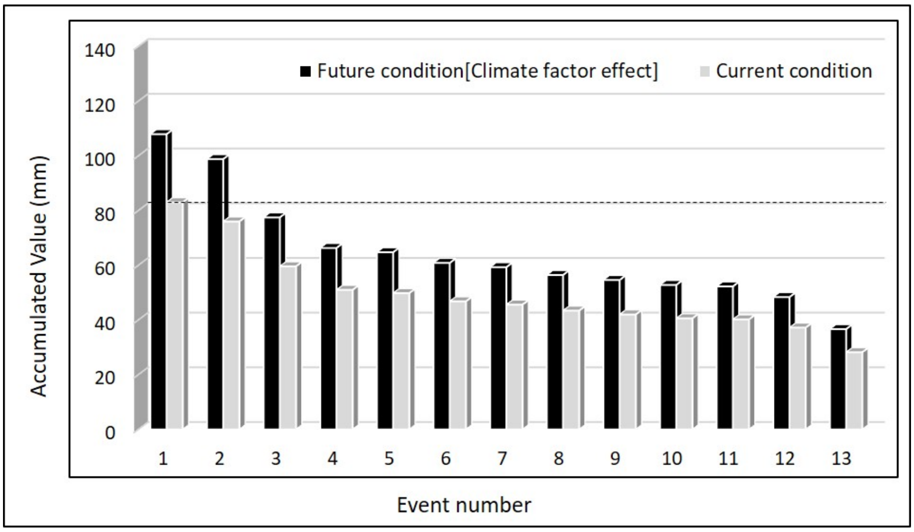

Figure 8.1: Comparing between the current and the future yearly return period.

It can be noticed from the figure 8.1, that the increase in the frequency of extreme precipitation can be detected. The rain event that has a return period of 30 years based on the accumulated value is going to accrue more frequency in the future as the criteria surpass the accumulated value approximately 2 to 3 times.

8.2.1 Passive Control Scenario Result in the Future Condition

The result of this simulation shows that the current channel is sufficiently capable to store the stormwater during the extreme rain events in the future condition and capable of containmening the runoff from the surrounding catchment in order to reduce the extent of the flood as can be seen in figure 8.2 and figure 8.5.

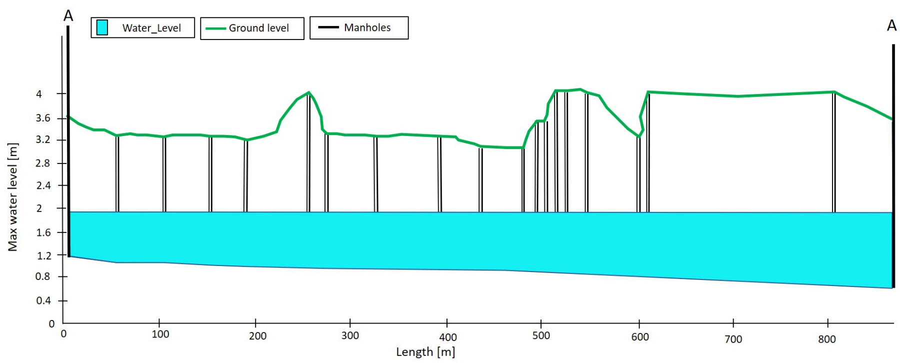

Figure 8.2: Longitudinal section A-A (Section A-A is illustrated in figure 6.10) shows the maximum water level in the old channel in the passive control scenario in the future condition.

8.2.2 Local Control Scenario Result in Future Condition

The result of this simulation shows that the detention basin, in the form of a basketball court is an effective way to reduce the flood. The longitudinal section A-A and B-B in figures 8.3 and 8.4 show a sustainable water level in the streams and this approve that the water level in the streams is much related to the water level in Limfjord than the rain intensity.

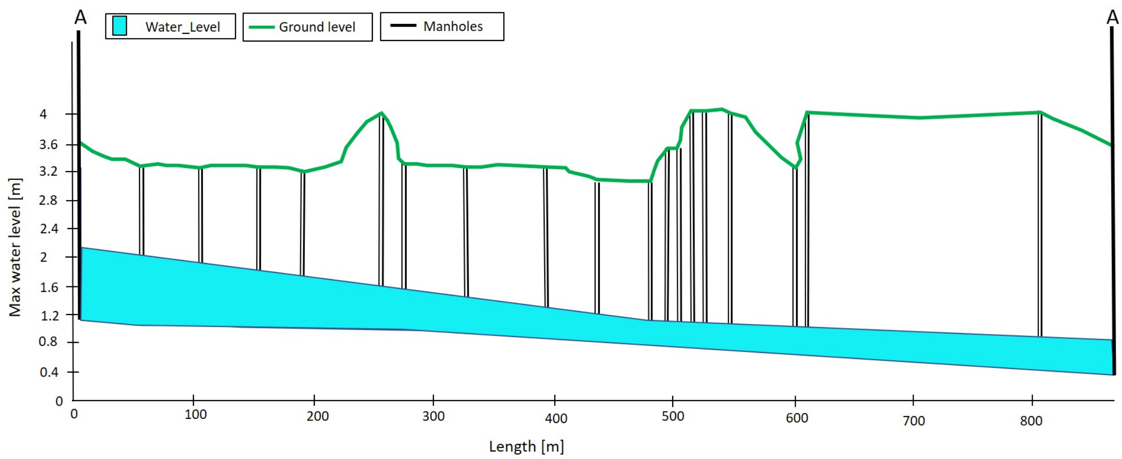

Figure 8.3: Longitudinal section A-A (Section A-A is illustrated in figure 6.10) shows the maximum water level in the old channel in the local control scenario in the future condition.

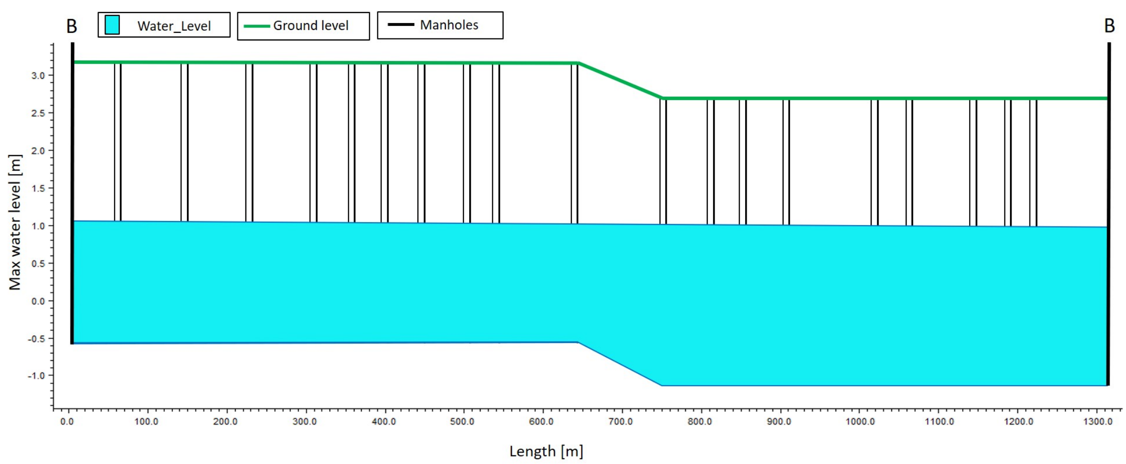

Figure 8.4: Longitudinal section B-B (Section B-B is illustrated in figure 6.10) shows the maximum water level in the new channel in the first and second scenario in the future condition.

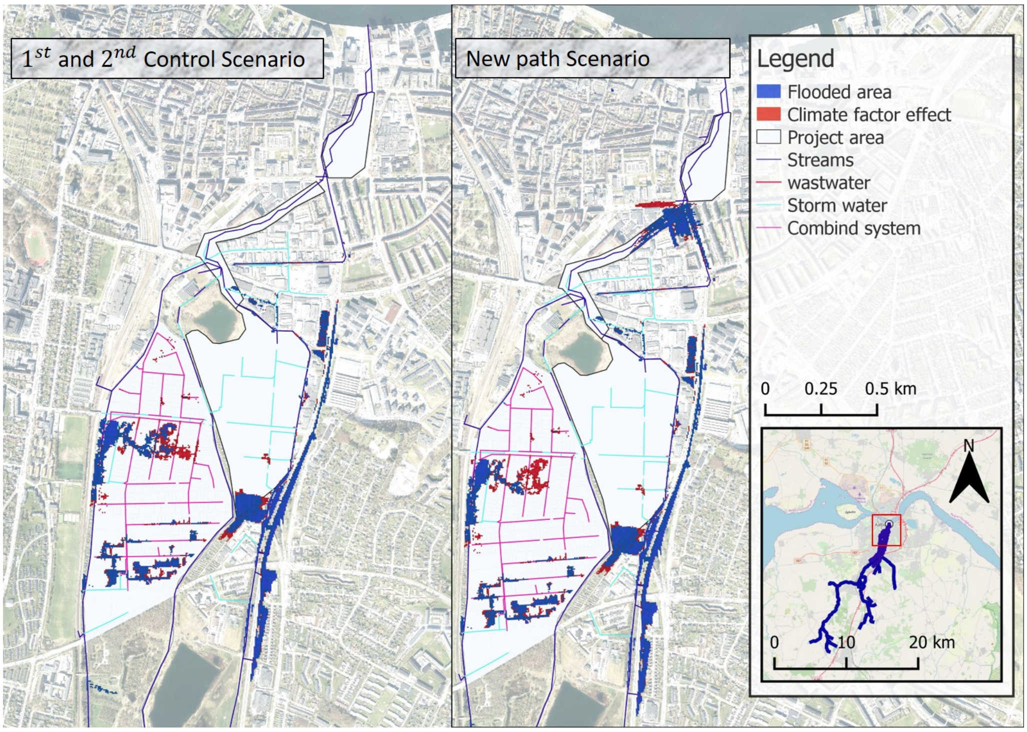

Figure 8.5: Comparing between the flood prone area in the new path scenario before and after the implementation of the first scenario caused by event 1. The implementation of the second scenario also shows same result as can be seen on the left side of the map.

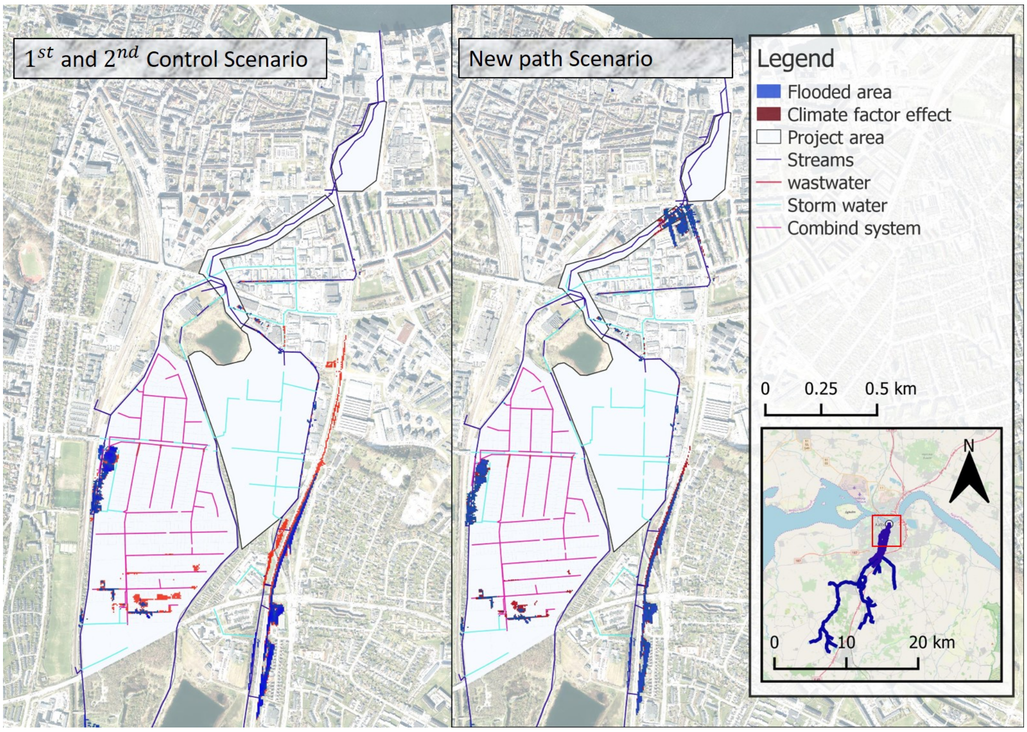

Figure 8.6: Comparing between the flood prone area in the new path scenario before and after the implementation of the first scenario caused by event 13. The implementation of the second scenario also shows same result as can be seen on the left side of the map.

As the climate factor has a major effect on the frequency of extreme precipitation, this may affect the need to use the new basin and increase the total cleaning cost. A brief overview is made to investigate the effect of the climate factor on the new basin and to determine the frequency of the needed cleaning. The investigation is made based on the comparison between the discharge in Link A and Link B and the water level in the new basin as illustrated in figures 7.6, 7.7 and 7.8.

To determine the return period of the new basin, every rain event in table 5.1 is tested in Mike Flood Model. The result shows that all the chosen rain events required the utilize of the new basin. Both event 1 and event 13 are presented and the result can be seen in figures 8.7, 8.8,8.9 and 8.10.

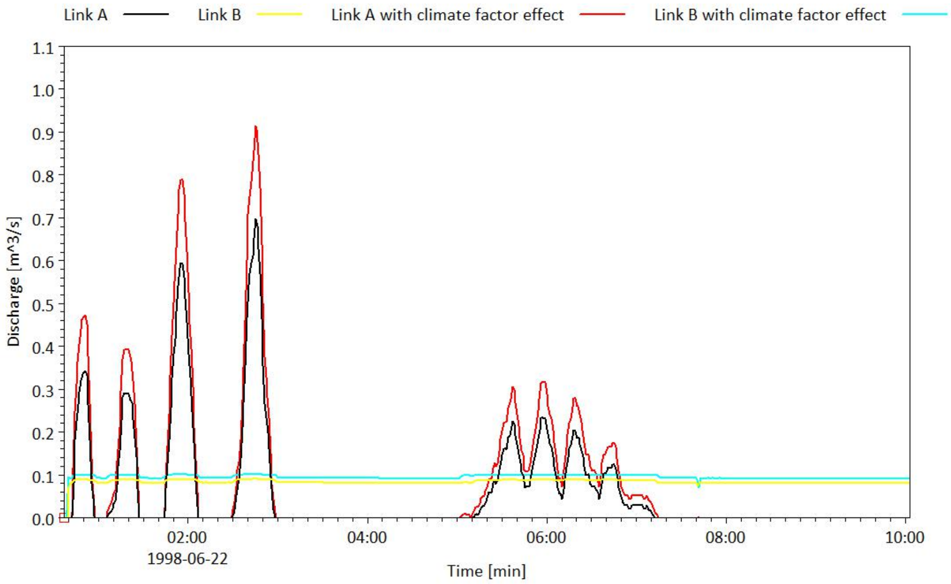

Figure 8.7: The discharge in link A and Link B caused by event number 1 with and without the climate factor effect.

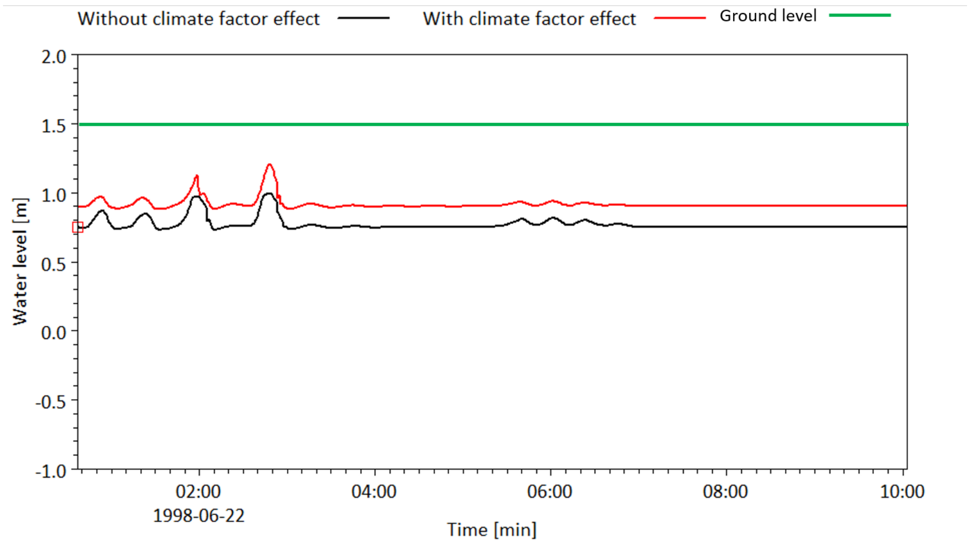

Figure 8.8: The water level in the new basin caused by event number 1 with and without the climate factor effect (Link A and link B is illustrated in figure 7.6).

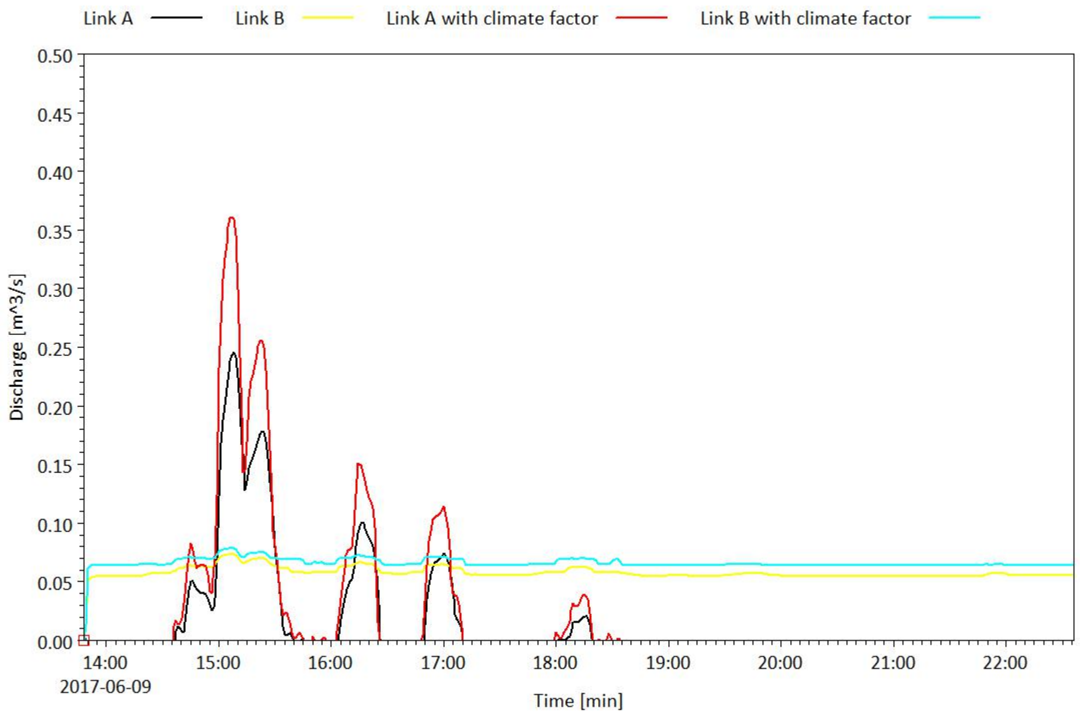

Figure 8.9: The discharge in link A and Link B caused by event number 13 with and without the climate factor effect.

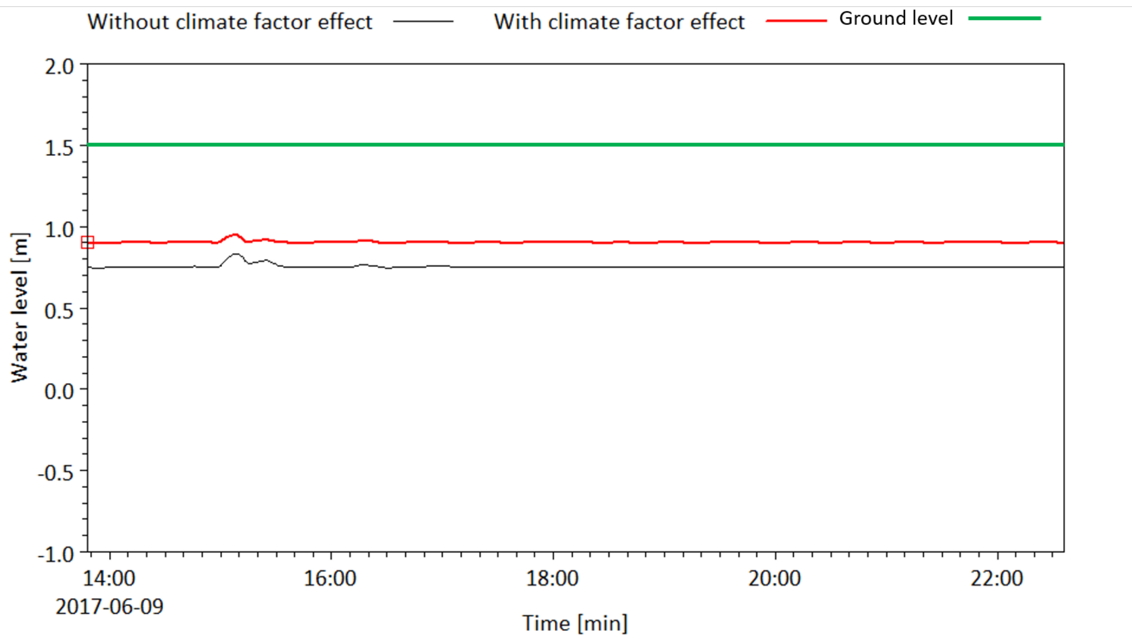

Figure 8.10: The water level in the new basin caused by event number 1 with and without the climate factor effect (Link A and link B is illustrated in figure 7.6).

For more investigation the model has been run for more rain events with different rain depth, and two rain events are selected randomly to be presented as can be seen in table 8.3.

Table 8.3: Additional rain events

Event number	Starting date	Ending date	Accumulated value (mm)	Yearly return period
14	3/25/2015 12:17	3/25/2015 23:56	22.68	0.5
15	8/31/2015 16:48	8/31/2015 23:59	14.9	0.2

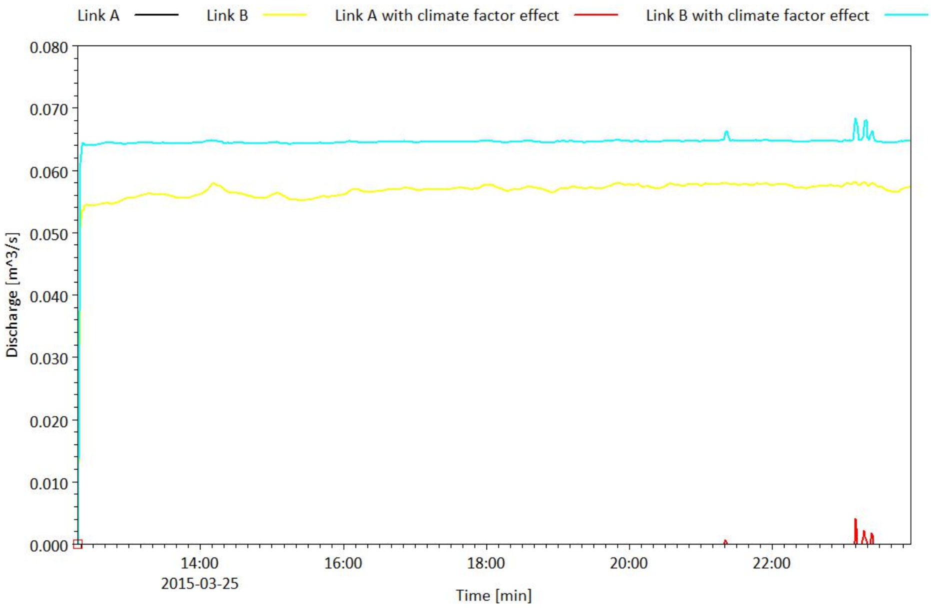

Figure 8.11: The discharge in link A and Link B caused by event number 14 with the without climate factor (Link A and link B is illustrated in figure 7.6).

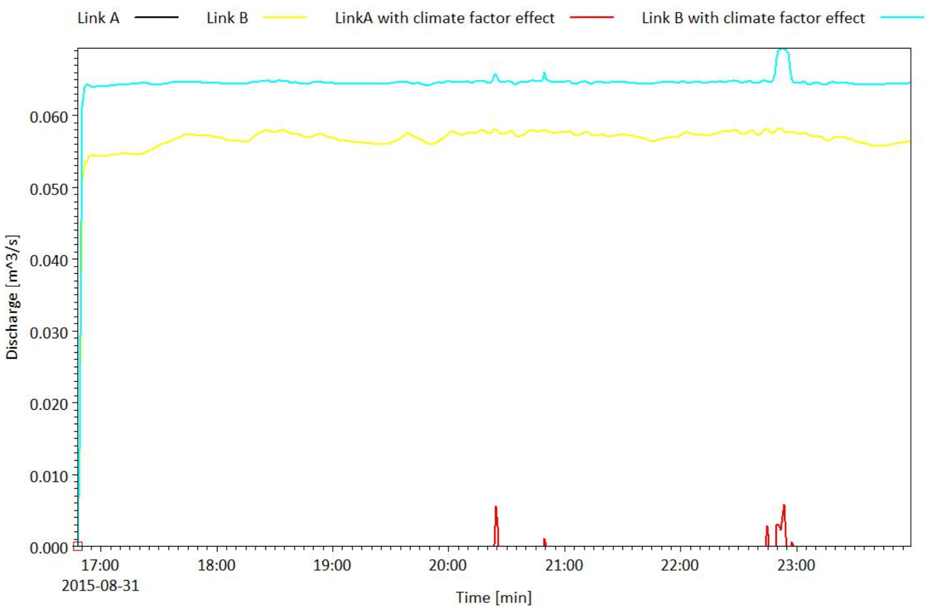

Figure 8.12: The discharge in link A and Link B caused by event number 15 with the without climate factor (Link A and link B is illustrated in figure 7.6).

Figures 8.11 and 8.12 show that both events are not required the utilize of the new basin, where the water level in the new basin during the rain events is zero. Based on the results it is assumed that new basin is required to be used at least once per year in the current condition and to be uses more frequency in the future condition as the climate factor effect start to appear in event 14 and event 15 as can be seen in figure 8.11.

IV Discussion and Conclusion

9. Discussion

This chapter contains a discussion of some of the uncertainties connected to the selection of the rain events, the boundary condition, models and assumption done in relation with the project work. In this project, the opening of the new channel of Østerå through Godsbanearealet and Karolinelund has been investigated to check whether such a change may have a significant impact on the flood risks in current or future condition. It is known that the area is heavily influenced due to many different conditions described in chapter 2 which made the area a matter of flood issues and consequently lead to cause urban flooding. The aim of the project is to detect the potential flood and manage to contain the flood prone area afterward. The challenge is undertaken by employing two different modeled solutions while presenting their efficiency, sustainability and availability. Proposed solutions are tested by implementing them into the Urban Drainage and Flood Model. Firstly, a short summary of the model boundary is presented. Later in this chapter, a more detailed discussion on the proposed solutions to solve and mitigate the problem is presented.

9.0.1 The Boundary Condition

- The choice of the Rain Events: The selection of 13 rain events from a 31 year period enables us to assess the drainage system for event having a return period of approximately 1 year which is the critical return period that the combined sewer system is designed for. The result of such event shows a flooding in the western part of Kærby as can be seen in figure 6.9. This is obviously under the assumption that no events with higher return periods than 31 years have been measured during the observation period. The result shows that the area is a matter for flooding issues as explained in chapter 2 and confirm the need for optimizing the total drainage system. And the plan of converting the combined sewer to a separated one might have a positive impact on Kærby in the future.
- The streams and Limfjord: The interface between the sewer system , Østerå and Limfjord is the key aspect of the exceeding flow that causes the flood. And providing ideal boundary conditions to present this reality is an impossible task and calculating the degree and extent of such interaction is complex. While in reality, many forces might affect the boundary such as the local wind, weather patterns, the tides and Coriolis's forces....etc. Therefore, using the observed data is necessary in order to improve the performance of the model as possible.

9.0.2 The Uncertainties of the Implementation of the New Path

Since the new path is not yet implemented in the reality, the planed dimensions are still unknown. There are some uncertainties of how the dimensions of the new path have been determined. In this project the dimensions of the path are determined based on some architecture plan, the current path and the previous part of Østerå as illustrated in figures 6.2, 6.4 and 6.3. This assumption can strongly affect the risk assessment result accuracy. Another uncertainty of implementing the new path is the manning roughness. The manning roughness is determined based on the roughness in the current path and the previous part of Østerå as can be seen in table 6.1. The flow velocity is strongly dependent on the resistance to flow, since the channel flow rate decreases as the Manning's number increases. Therefore, these assumptions that have been made can greatly affect the model result efficiency. These assumptions might not be the most accurate, but it is deemed a good approximation and it has therefore been considered valid for its use of the model. However, the water level in the new path obtained after the simulation is found to be stable against the extreme rain events as well as the Limfjord effect and therefore, these assumptions are to be sufficient and recommended.

9.0.3 Urban Drainage and Flood Model

The coupled 1D/2D models are essential since they are able to outline the different interactions between drainage system, runoff and surface flow dynamics. As mentioned earlier, calculating the degree and extent of such interaction is complex and resource consuming but recently the modelling software has made it easier to asses. The flood models enable us to identify the flood prone areas which can be crucial to a better understanding of surface flood dynamics. It allows initially focusing on the areas where most attention is needed and consequently increasing the adequacy of stormwater management of urban drainage systems under heavy rainfall.

9.0.4 New Path Scenario

Model of the new path scenario shows a satisfactory result, the implementing of the new channel of Østerå has a significant impact on the flood cost as can be seen in figure 6.18. This is considered a positive change, especially by decreasing the flood in the residential area in Karolinelund which is the most expensive in the project area. Even though the result still shows some flood prone area insuring the need for a management plan to avoid the flood consequences.

9.0.5 The First and Second Control Scenario

The sustainable urban developments have been an important and a discussed subject recently in Denmark, as many cities in the world are trying to build more sustainable urban area. In this project two sustainable approaches based on a passive and on an active control scenario are tested in Mike Flood Model in order to handle the flooding caused by the residential area as seen in figure 7.2.

- The Passive Control Scenario: Using the total volume of the current path to store the runoff from the residential area during the rain events and hold a specific volume of water is sufficiently capable of reducing the flood. But since there is a proportional relation between the water level in the streams and Limfjord, a storm surge in the Limfjord together with high rainfall intensities might disrupt the idea of using the old channel as a storage basin and might effect the capacity of the channel during the extreme events.
- The Local Control Scenario: This scenario has proved to be the most sustainable solution due to the fact that on one hand, converting of the combined sewer to a separated system is already planed according to the Aalborg municipality and since the municipality has the intention to complete the plan, that makes the idea of driving the stormwater from the

residential area through pipes to a small basin in Karolinelund is possible to implement and available. On the other hand, the location of the basin is not connected directly to the streams and to Limfjord which makes the basin in Karolinelund less affected by the backwater from Limfjord during the extreme events.

The local control scenario is required to install a sensor and such sensors have to be resistant to long term physical and chemical attack, because the presence of sensors in the foul environment of drainage systems requires additional equipment for cleaning of the instrumentation. The sensor should be cheap and easy to use and to maintain without affecting the performance quality. Despite the advanced technology of the RTC in overall optimization is better and more flexible in order to control the drainage system, still there is a reluctance of wastewater operators to introduce advanced technology in wastewater systems which is still perceived as complex. Therefore, the second scenario is investigated to see whether it is possible to be implemented based on a passive control system as the first scenario by using a simple regulator outlet as a water break instead of using the sensor. After implementing the new scenario in Mike Urban and run the simulation, the result shows a similar result which confirms that it is possible to use the passive control. The scenario model can be seen in electronic appendix E.The advanced technology of the RTC is an effective tool that can be useful and can be used in the future. Converting the combined sewer to separated systems in order to handle waste and stormwater within the municipality will increase the discharge Load in the streams and therefore, the need for retained basins to store the stormwater during the extreme precipitation and discharge it slowly is arising. The global control system can be used to optimize the drainage system by implementing a sensor in each basin as well as in the new and the current channel and then connect all the sensors to a control center device.

10. Conclusion and Recommendation

The opening of the new path of Østerå in Aalborg is investigated to detect the hydraulic consequences on the project area. The flood risk assessment of such plan shows satisfactional results in order to reduce the extent of the flood and decrease the flood cost in Godsbanearealet and Karolinelund. The result shows that the new path does not increase the flood risk in Kærby, hence the new path of Østerå can be implemented according to the design suggestion presented in chapter 6.

Until recently, sustainability has become more and more important. Many cities in the world are trying to build more sustainable urban areas where both rain and runoff-flow can be handled locally and so is the case in Aalborg. Two sustainable approaches based on a simple control system are suggested in this project. From the result, it can be concluded that it is possible to handle the flooding caused by the runoff-water from the residential area through the implementation of the control system. Hence, if the flood risk near Karolinelund is to be reduced, the detention basin based on either a passive control or a local control system which presented in chapter 7 is an available solution.

Furthermore, it is found that the effect of the new path plan of Østerå on the district of Kærby to be worthless. Moreover, although both control scenarios are an effective tool to control the flood in Karolinelund, it is found to be insignificant for reducing the flood in Kærby. However, providing a similar tool to the reactive control scenario by implementing a detention basin, in the form of a basketball court, might be capable of reducing the extent of the flood in Kærby.This suggestion should be considered for other studies.

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V Appendix

A. Input Data in Mike Urban Model

A.1 Østerå Input Data

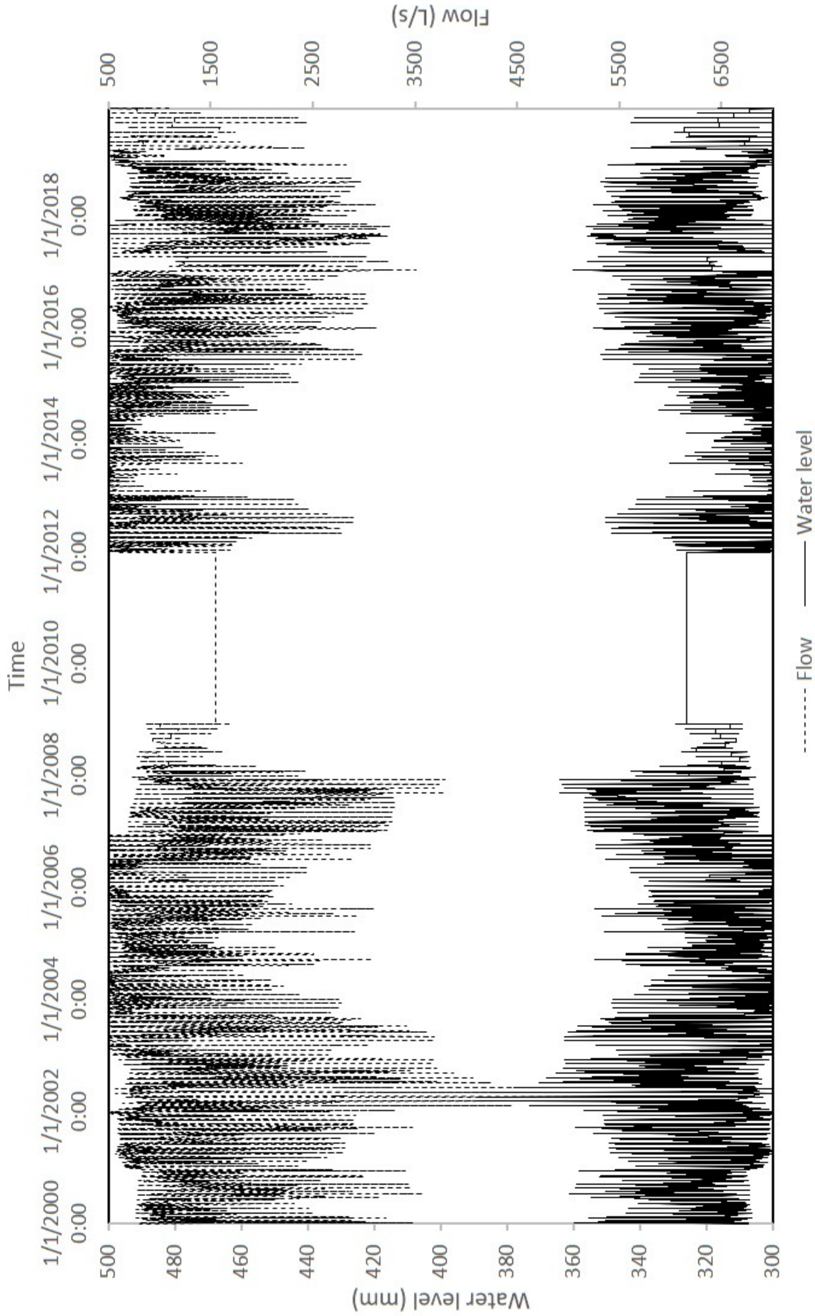

Figure A.1: The flow boundary and the water level in Østerå.

A.2 Limfjord Input Data

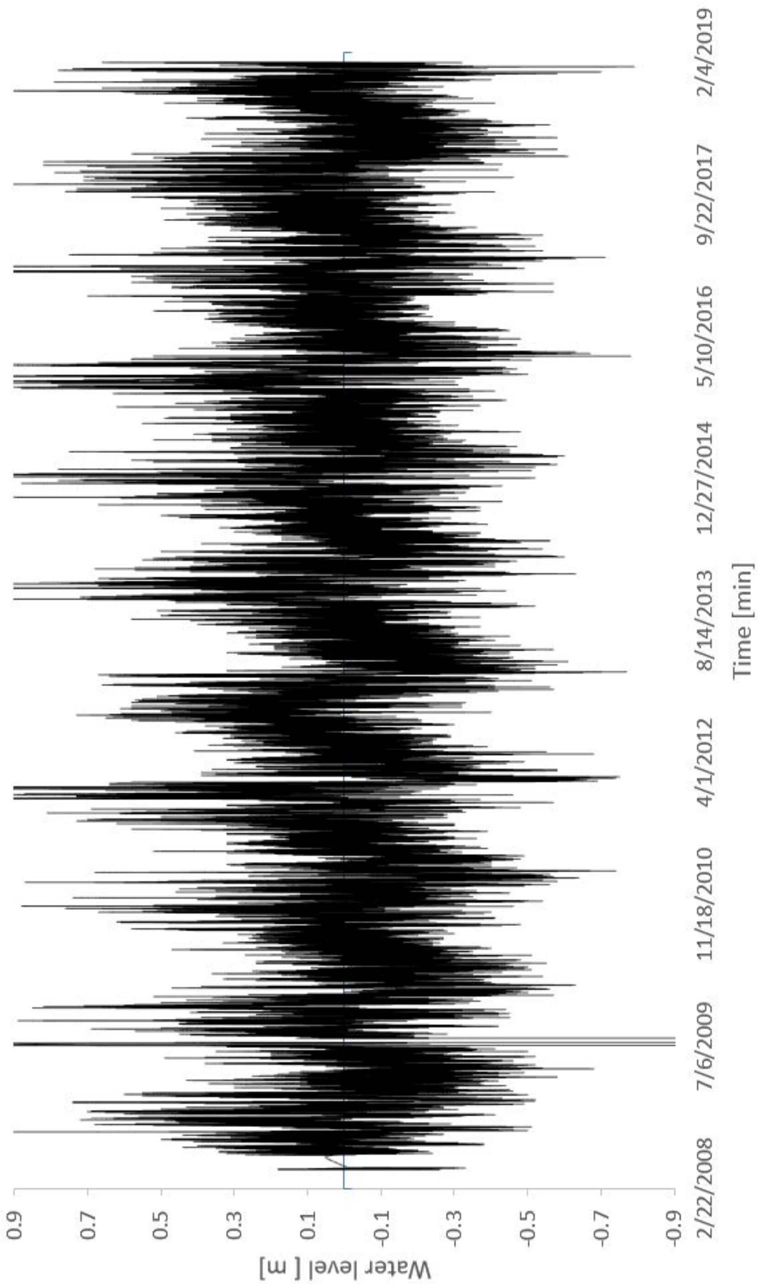

Figure A.2: The water level in Limfjord.

A.3 The Precipitation Input Data in Mike Urban Model

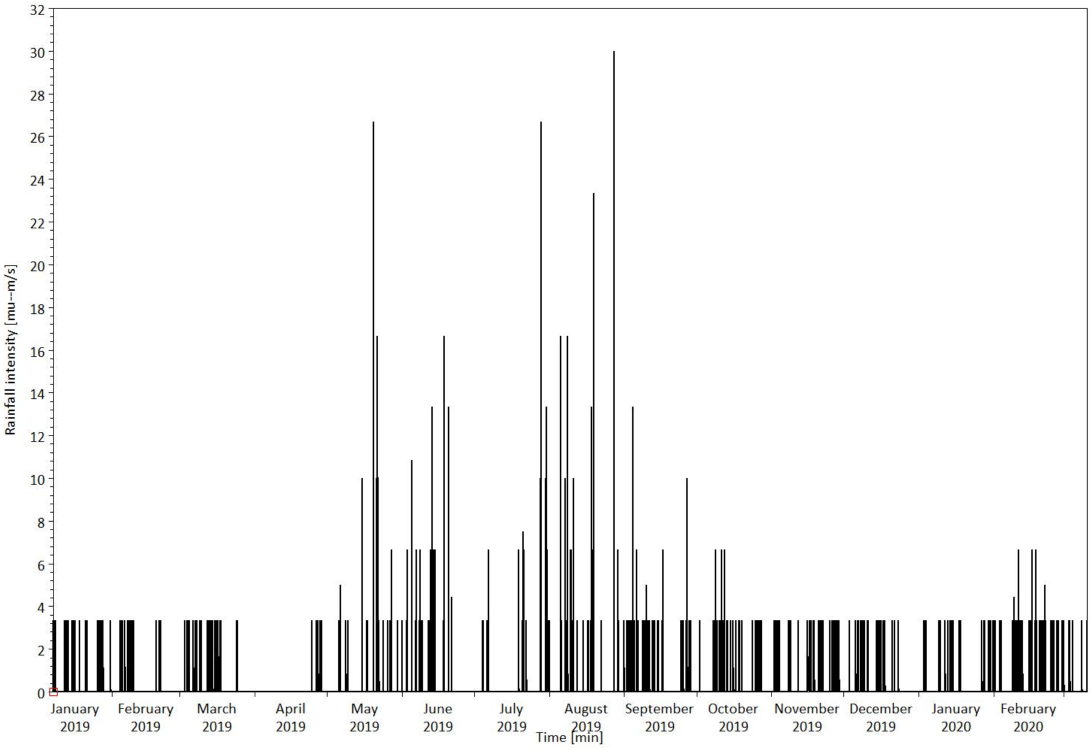

Figure A.3: Historical rainfall series of period from 2-28-1990 to 10-3-2020, measured at Østerport rain gauge.

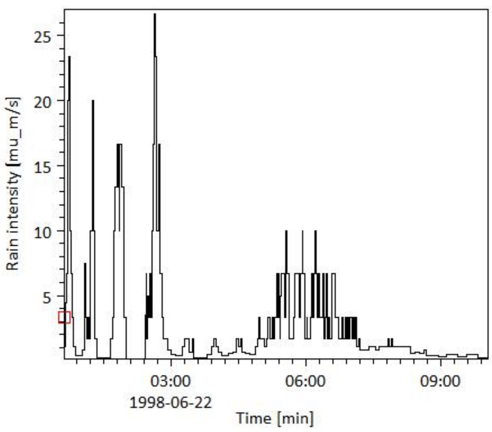

Figure A.4: Event 1.

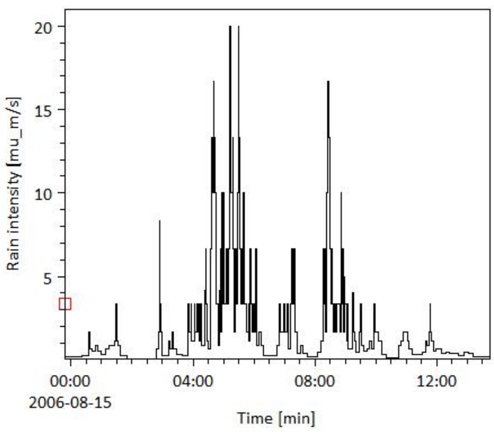

Figure A.5: Event 2.

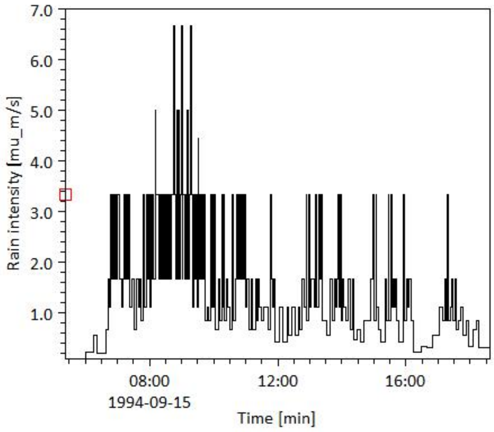

Figure A.6: Event 3.

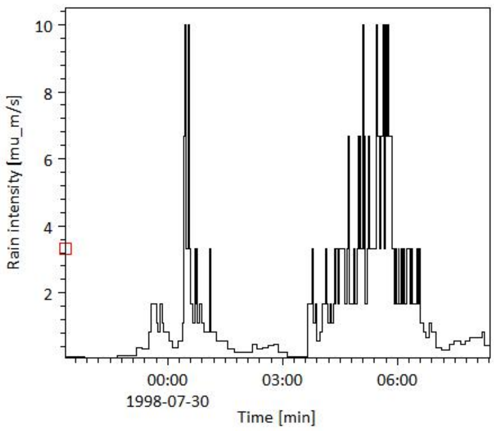

Figure A.7: Event 4.

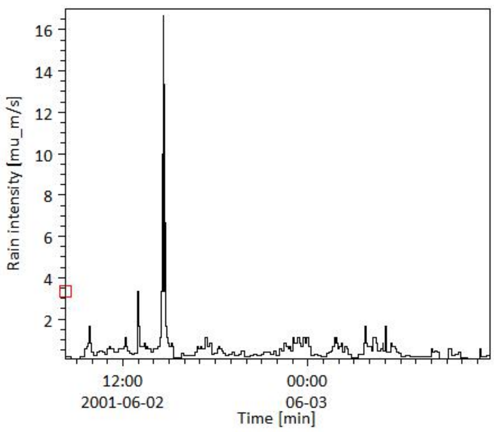

Figure A.8: Event 5.

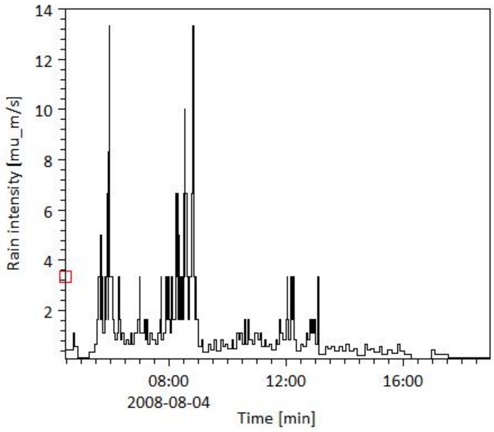

Figure A.9: Event 6.

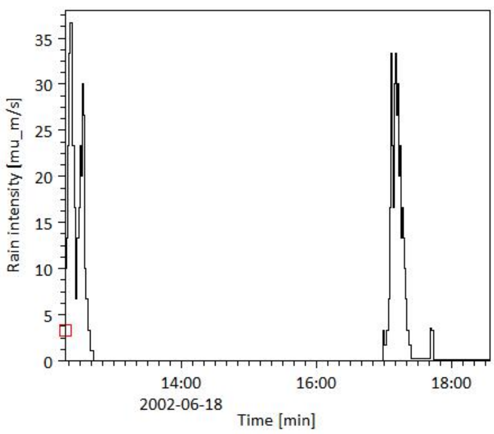

Figure A.10: Event 7.

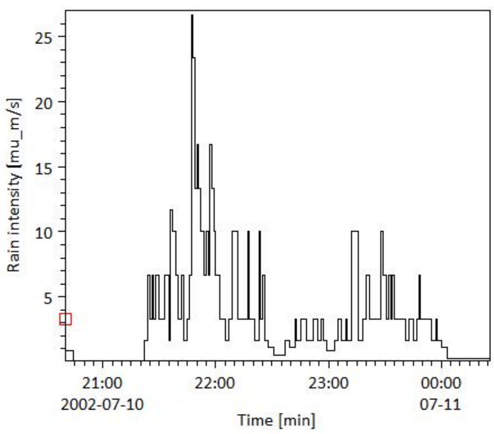

Figure A.11: Event 8.

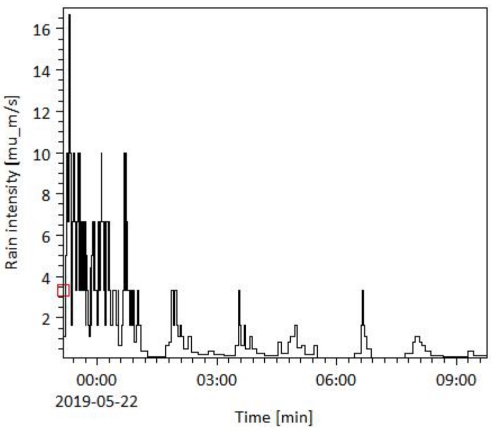

Figure A.12: Event 9.

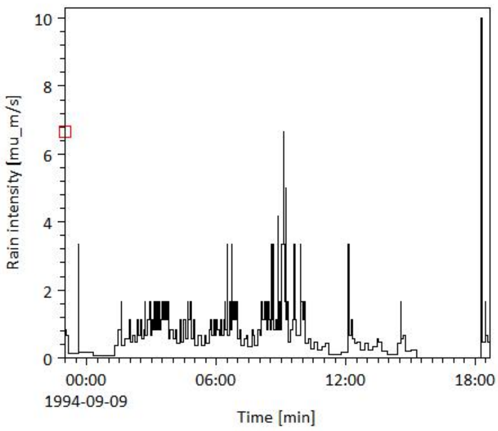

Figure A.13: Event 10.

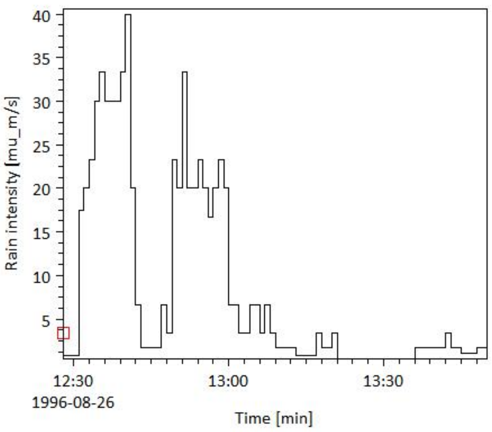

Figure A.14: Event 11.

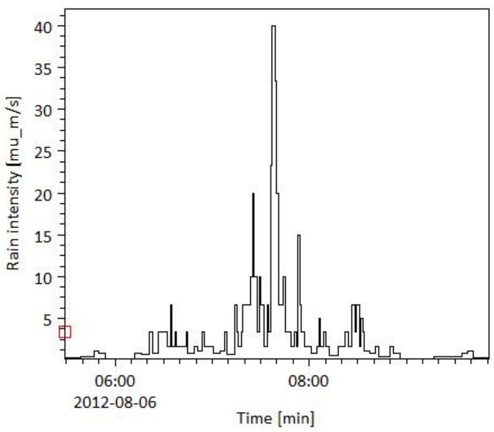

Figure A.15: Event 12.

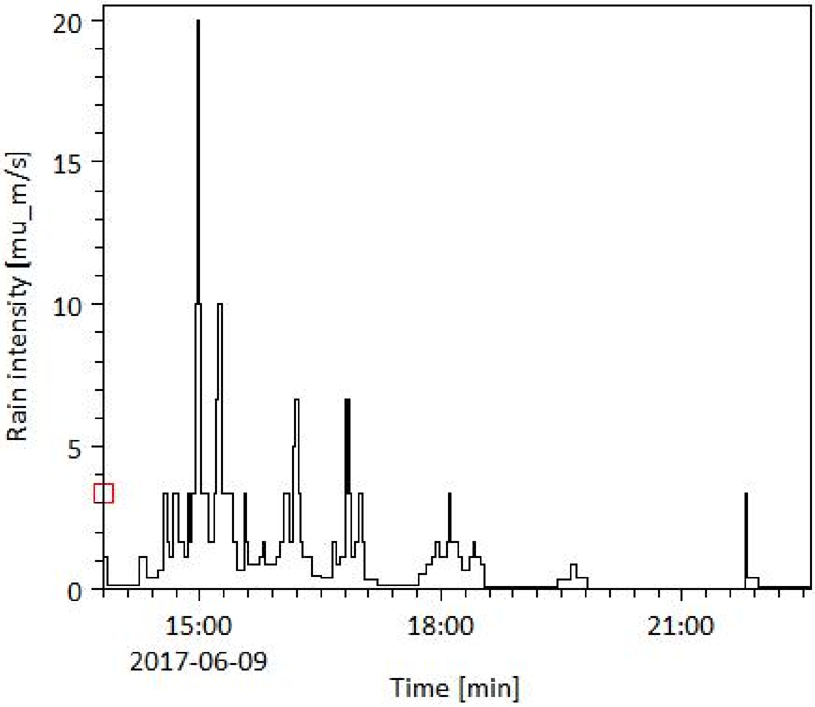

Figure A.16: Event 13

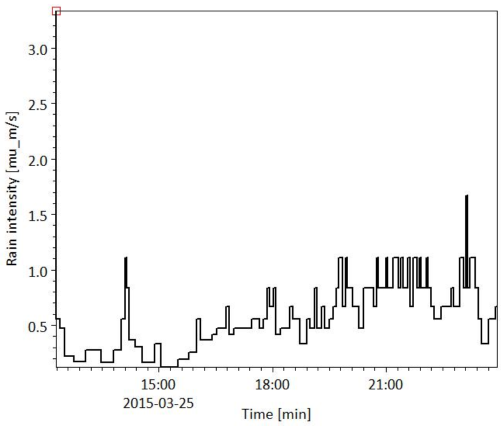

Figure A.17: Event 14.

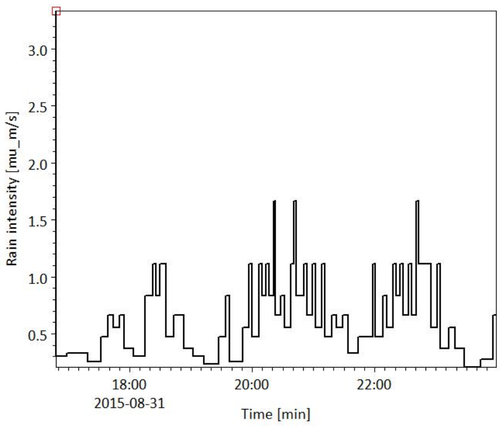

Figure A.18: Event 15.

B. Sensitivity Analysis of the Grid Size in the Model

In regard to the grid size in Mike Model, a sensitivity analysis of the grid size has been made to determining the grid size. The analysis performed thought two criteria: the time consumption and the flooded area. Based on the result in figure B.1, a grid with resolution of 5x5 m^2 is chosen since this point is located in a position where the flooded area became a constant and in reasonable time consumption.

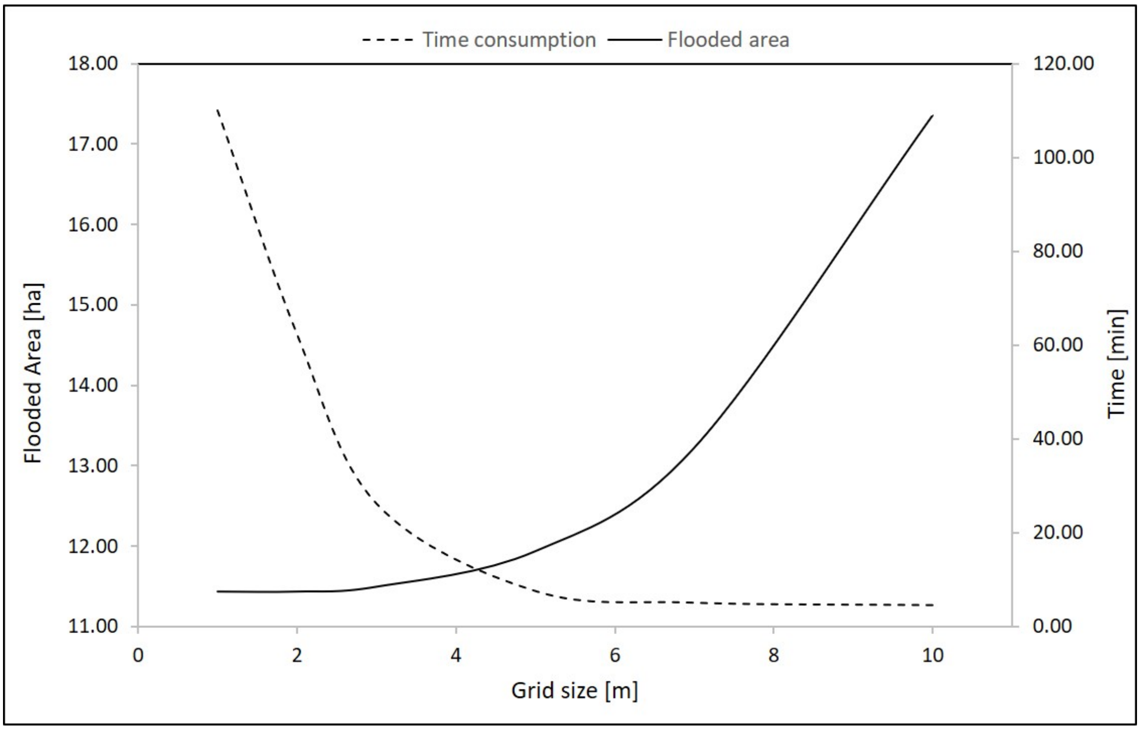

Figure B.1: The sensitivity analysis of the grid size obtained after the simulation of a random rainfall event in Mike Flood Model.

C. Estimation of the Flood Damage Cost

As mentioned earlier in section 6.5, only the land use has been taken into consideration in this project in order to calculate the flood damage cost. This is done by using an estimation map from [Miljø- og Fødevareministeriet - Miljøstyrelsen, 2013] as can be seen in figure C.1. The focus on this map is more on the construction costs and expenses for operation and maintenance. The flood damage to buildings and contents are dependent on several variables as the type of building structure and construction, and the materials of which they are made have a big influence on the nature and extent of damage caused by the flood.

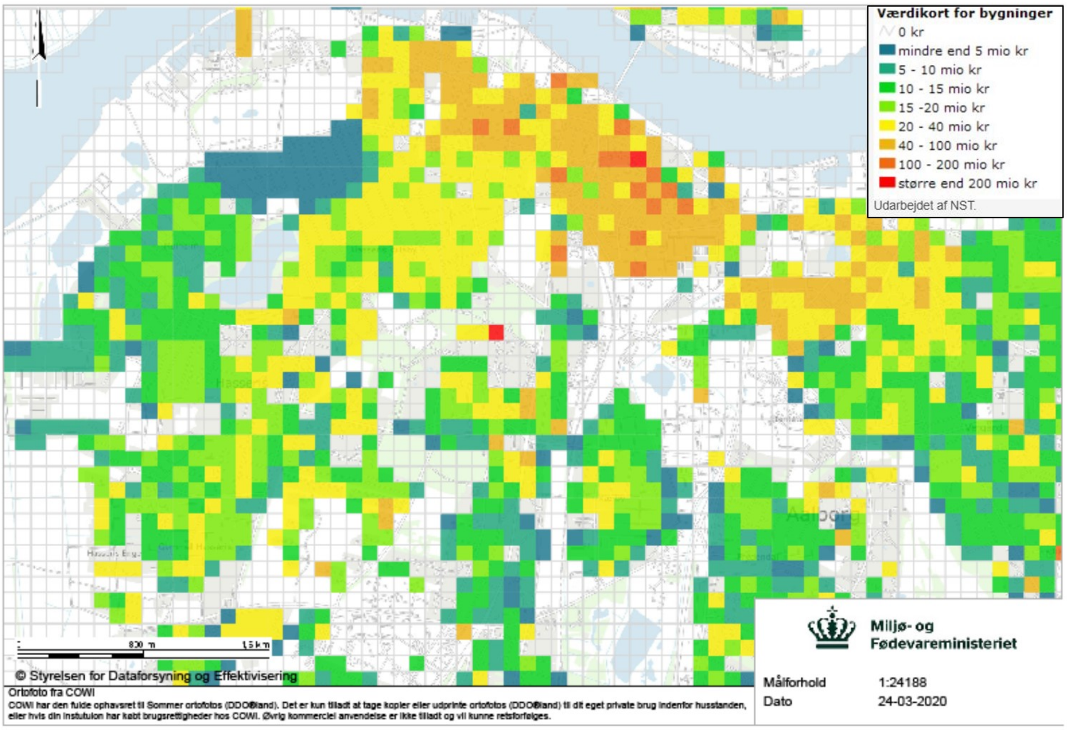

Figure C.1: Estimation of flood damage cost [Miljø- og Fødevareministeriet - Miljøstyrelsen, 2013]

D. The Project Site

The following appendix shows photos of the current project area. An overview map of where the pictures were taken is shown in Figure D.1. The map includes 17 sites presenting the main streams, the weir, Østerådalen, Åparken, Karolinelund and the outlet in limfjord. The photos were taken in a period between November 2019 and May 2020.

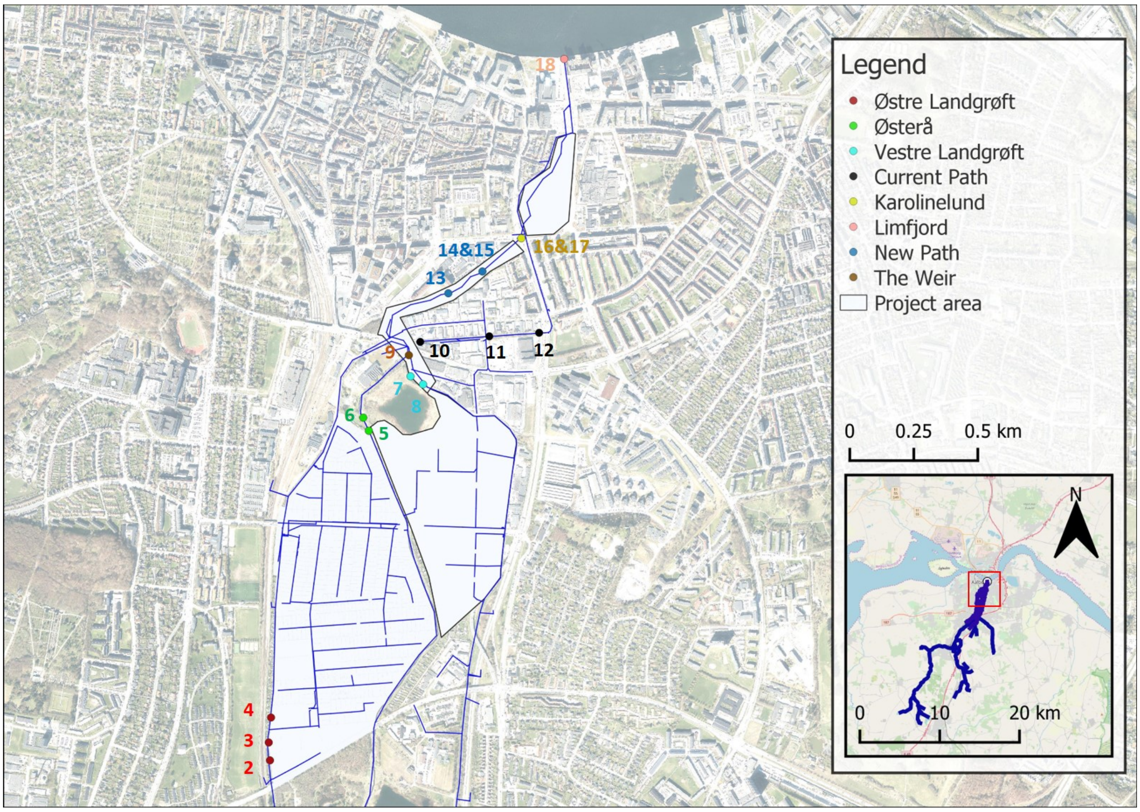

Figure D.1: The photos positions, where the photos were taken. NB: The photo number is reference to the figure number (Figure D.$_{Photonumber}$).

D.1 Vestre Landgrøft

Figure D.2: The open channel of Vestre Landgrøft.

Figure D.3: The location where Vestre Landgrøft transform from open channel into pipe line.

Figure D.4: The pipe line of Vestre Landgrøft. A manhole sets for each 10 m along the stream.

D.2 Østerå

Figure D.5: Østerå.

Figure D.6: A small pip discharge the runoff from a residential area to Østerå.

D.3 Østre Landgrøft

Figure D.7: Øster Landgrøft.

Figure D.8: Øster Landgrøft.

Figure D.9: The weir, where the three streams meet. This point is the inlet discharge to the new path of Østerå.

D.4 Østerådalen

Figure D.10: The location of the inlet discharge to the current path.

Figure D.11: The current channel.

Figure D.12: The location where the current channel change from open channel into pipe line.

D.5 Godsbanearealet

Figure D.13: Godsbanearealet. The area has not been used for the past 10 years and now it is covered with grass and construction materials.

Figure D.14: Godsbanearealet.

Figure D.15: Godsbanearealet.

D.6 Karolinelund

Figure D.16: The currently undergoing maintenance work in Karolinelund.

Figure D.17: The currently undergoing maintenance work in Karolinelund.

D.7 Limfjord

Figure D.18: The outlet discharge to Limfjord.

E. Electronic Appendix

E.1 Boundary Condition Data

E.1.1 Østerå Data

E.1.2 Limfjord Data

E.1.3 Rain Data

The Selection of the Rain Events

Rain Events

E.2 Current Path Scenario Model and Result

E.3 New Path Scenario Model and Result

E.4 Passive Control Scenario Model and Result

E.5 Local Control Scenario Model and Result