Master Thesis

Analysis of urban catchment for flood return period assessment

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Synopsis

The present project deals with the analysis of a specific urban catchment in order to assess the return period of flood events based on flood depth, flood volume and flood extent. Extreme rainfall events is the main cause of flooding in Denmark during the last decades. Some extreme events are selected from historical rain series to assess flooding in the chosen catchment. The selected catchment has the characteristic of having large terrain variability, with some flat and steep areas and it is set in this project as an irregular catchment. The relationship between the return period of flood and the return period of rainfall is analysed and discussed in this project, since a variable rainfall is applied in an irregular catchment.

In order to do the analysis of historical flood events, flood modelling is used to simulate 10 extreme events from 1989 until 2016 and later on obtain the maximum flood depth, maximum flood extent and maximum flood volume for assessing the return period of flood.

The report find a weak relationship between the return period of rainfall and return period of flood depth and flood extent and a better relationship with the return period of flood volume.

Preface

This project has been written at the faculty of Engineering and Science at Aalborg University during the spring of 2016. The project has been written by Laura Casas Cardona, currently studying at the 4th semester of the Master's program Water & Environment.

The project is an analysis of an urban catchment for assess the return period of flood. The project lasted from spring 2016 to the date of submission 7 June, 2016. For making this project, a special gratitude goes to the supervisors, Søren Liedtke Thorndahl and Damià Murlà Tuyls who have assisted with guidance and ideas.

Reading instructions

The report is divided into sections and subsections. In this way, it will be easier to refer to. For each figure and table may be present in this report, these are numbered by order.

Additional information are placed in the appendix, which is after the bibliography list.

The bibliography contains the list of literature, which is referred to through the entire report. The citations in the report are presented as author-year citations, which is the Harvard method.

Laura Casas Cardona

Abstract

The purpose of this study is to analyse an urban catchment for assessing the return period of floods. Denmark has been affected by extreme rainfall events in the last decades causing high environmental and social impacts which lead to social and economic losses.

This study is focused in the use of historical rain series to analyse the relationship between the return period of flood and the return period of rainfall.

The catchment under study has a large terrain variability which is considered to be irregular since it comprises steep and flat areas, complex flow in drainage systems and on surface. From the historical rain series, a selection of 10 extreme rainfall events are chosen and simulated to study and analyse their flood.

At the end of the document are discussed the obtained results analysing if the use of historical rain series is more appropriate than the use of synthetic rain for flood modelling. Furthermore, the maximum flood depth, maximum flood extent and maximum flood volume of the catchment are found for each of the events and then discussed to determine which of these variables is the most accurate to assess the return period of flood.

Danish abstract

Nærværende projekt omhandler analyse at et specifikt urban afløbsopland og har til formål at kunne bestemme gentagelsesperioden for oversvømmelseshændelser ud fra lokal oversvømmelsesdybde, oversvømmelsesvolumen og oversvømmelsesudbredelse. Igennem de sidste årtier er ekstreme regnhændelser hovedårsagen til oversvømmelser i urbane områder i Danmark. I nærværende projekt er ekstreme regnhændelser udvalgt fra historiske regnserier og analyseret med hensyn til oversvømmelse på et konkret opland i Lystrup nær Aarhus. Oplandet er karakteriseret ved stor terrænvariabilitet, herunder både flade og for danske forhold relativt stejle områder. Derfor er oplandet karakteriseret som afstrømningsmæssigt irregulært. I projektet er sammenhængen mellem gentagelsesperiode for oversvømmelsen og gentagelsesperioden for regnen er analyseret og diskuteret. Det er konkluderet at der er stor variabilitet mellem gentagelsesperioden for regnen og gentagelsesperioden for oversvømmelsen. Derfor kan det være svært at karakterisere en oversvømmelse ud fra regnen alene.

Contents

1. Introduction

Flooding has become one of the main issues creating significant impacts to urban areas. Notably the problem is increasing rapidly and its consequences are manifested damaging infrastructures and properties. Urban floods are generally caused by local extreme rainfall where the flow exceeds the capacity of a pipe, which gets pressurized, leading to surface flooding. The extent of floods mainly depends on the spatial-temporal variability of rainfall, the size of the catchment and the soil characteristics (Ochoa et al. 2016).

Return period and duration of rain are the most common variables used for rainfall analysis. Return period of an annual maximum storm event is determined through the largest event in a specific year and it is statistically independent of the largest one of another year (Davies, 2004).

One of the main concerns that has been discussed is the relationship between the return period of floods and the return period of Design storms e.g. Chicago Design Storm (CDS). According to the rational method: $Q= i \cdot A_r$ there is a linear relationship between the rainfall intensity for a given return period and rainfall duration (aggregation time) in a pipe. However, whether this relationship is valid during surcharging of pipes, flow on surface, etc. is doubtful. CDS is a common method for generating synthetic hydrographs for the design of rainfall and it is based on Intensity, Duration and Frequency (IDF) curves (Thorndahl, 2015).

However, the mentioned relationship may not happen in complex urban drainage systems, where elements as overflow basins, pumps or other hydraulic infrastructures increase the system heterogeneity. In those cases, the topographic features of the catchment, must be considered. For instance, regions with a flat topography and where a constant rainfall is applied, a good correlation may occur. However, in a steep and irregular catchment, water flows downhill where it is stored on the surface throughout the catchment. In that case, the linearity between return periods may probably not occur. Hence, the use historical rain series instead of CDS is recommended as input for flood simulations, since the latter may overestimate flood depth and extent (Thorndahl, 2015).

In that sense, flood modelling tools have been widely used to analyse historical floods or to predict future floods and climate change scenarios (Thorndahl, et al. 2016). In this study, the rainfall-flood relationship is analysed under different conditions in a specific catchment.

2. Objectives

An analysis is done to study possible irregularities on rainfall-flood relationship, applying historical rain series in a specific catchment. Moreover, the catchment response to its topographical and network features, when rainfall is applied, is also studied.

The return period of flood can be assessed by using different variables. In this study, it has been based on the local maximum flood level, maximum flood extent and maximum flood volume for the whole catchment. Two main analyses are done from a selection of events. First, the flood extent and flood volume of the catchment under study are compared and its correlation analyzed. Then, their return period is calculated and compared to the rainfall return period. The second analysis is based on the first results, 4 local points from the catchment are selected to analyze the maximum flood level for the selected events. The comparison between the return periods of maximum flood level and the return period of rainfall is done, where the aggregation time of rainfall in each point is estimated by calculating the time of concentration for each selected point. Moreover, the maximum flood extent, maximum flood volume and maximum flood level are compared to each other at the end.

Finally, results from both analyses are considered and the most appropriate variable to assess the return period of flood is determined.

The key questions to achieve the objective set in this project are:

- **Which differences are seen in flood depth, flood extent and flood volume considering an irregular catchment with steep and flat areas?**
- **Which relationship is seen between the return period of rainfall and return period of flood by applying historical rain series?**
- **How to assess the return period of flood?**

3. Literature review

3.1 Causes and consequences of floods

Extreme rainfall is the main cause of flooding and the main source for urban avenues, streams and rivers. The level of the rivers and streams rise and is one of the principal causes of floods. In addition, when the soil is saturated, so rainwater cannot be absorbed, water flows on the surface referred to as surface runoff (USGS Water Science School, 2016).

Urban development has greatly affected nowadays on the increasing of pluvial flooding in urban areas. Surface runoff has raised due to the removal of vegetation, in exchange of growing paved surfaces and to the construction of various drainage system infrastructures. During high intensity rainfall, urban drainage systems do not have the capacity to drain all the water, inducing to pressure flow in pipes and leading to surface flooding (Davies, 2004; Konrad, 2014).

Floods can cause high environmental and social impacts which lead to large economic losses. Some of these impacts include damage to vial infrastructures, private properties and materials and sometimes they affect directly to population, thus there is a need to analyse and minimize their sources and consequences.

3.2 Flooding in Denmark

In Denmark, most of the cities have been affected by very long-term extreme rainfall events which have resulted in pluvial flooding during the recent years. These events have raised awareness on flood management. Additionally, due to future climate change conditions an increase of high intensity precipitation is expected as well as a growth in population causing a higher exceedance of the drainage systems both in frequency and intensity (DHI, 2014; Arnbjerg-Nielsen et al., 2015).
According to Spildevandskomiteen (2005), there are some minimum requirements regarding the design calculation of the pipes from the drainage system in Denmark (European standard, 2008). The minimum functional requirements are:

- The return period for surcharging the critical level for combined systems is 10 years
- The return period for surcharging the critical level for separate systems is 5 years

Moreover, it is recommended for complex design models on steeply sloping catchment areas a return period of 1 in 20 years for residential areas and 1 in 30 years for city centres, industrial and comercial areas (Dansk standard, 2008).

3.3 Variables of rainfall

One of the main effects of urban development is the increment of peak discharges and in consequence the frequency of floods. Return period, duration and intensity are the main rainfall properties analysed throughout this study.

According to Davies (2004), it is often assumed that the rainfall and runoff frequency are equivalent. Even though it is not always correct since there are some conditions that are not the same for all rainfall events such as the soil moisture or spatial distribution of rainfall over the catchment. Another aspect to consider is the relationship between the return period of rainfall and the return period of flood which has been usually assumed to be equal by the use of design CDS storms. Nevertheless, when the drainage sewer system exceeds its capacity, water starts to surcharge, and surface flooding occurs, where water is transported throughout the surface (Davies, 2004).

Furthermore, rainwater is also accumulated in small depressions on the catchment as illustrated in Figure 1. Depression storage mainly depends on the topography, contribution area and slope, and on the rainfall characteristics. Other processes such as infiltration, evaporation and leakage also lead to reduce surface runoff, but are not considered in this study.

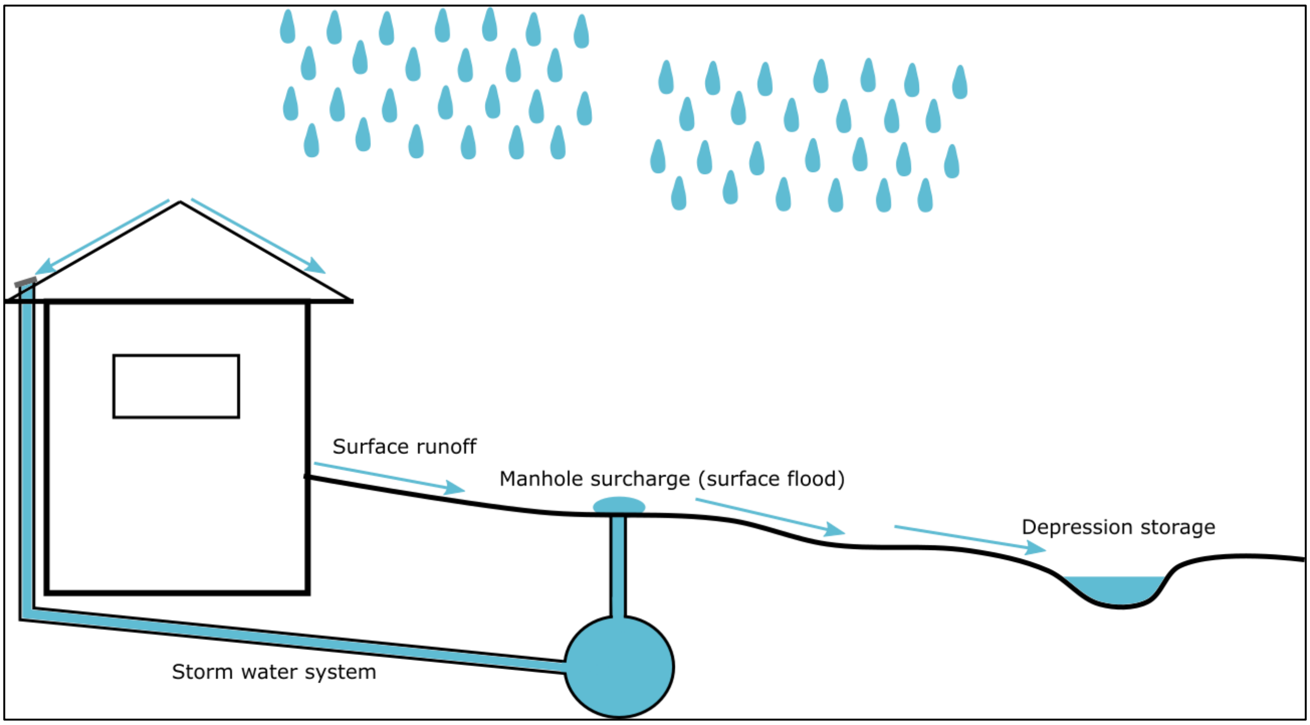


Figure 1: Urban drainage system scheme.

According to Viglione et al. (2009), rainfall intensity and storm duration, temporal and spatial patterns should be considered. Additionally, the flood return period is equal to the return period of rainfall when there is only a single storm duration, regardless of the unit hydrograph shape. In other cases, when the storm durations vary, the return period of flood is smaller than the return period of rainfall.

3.3.1 Time of concentration

The time of concentration is an important concept defined as the time used for water to flow from two points of the system. It is used to measure the response of a catchment in regards to a rain event, thus can be compute the peak discharge of a catchment (LMNO Engineering, 2015).

Several methods can be used to estimate the time of concentration. By applying the rational method, the time of concentration is used to select a rainfall intensity since the peak discharge is a function of the rainfall intensity. When the duration of the event is larger than the time of concentration, the rainfall intensity will be low, so the peak discharge will be underestimated. On the other hand, if the duration of the event is lower than the time of concentration, meaning that not all the water of the catchment is contributing to the runoff, the optimal value is not achieved. Thus, when applying the rational method, the duration of an event has to be equal to the time of concentration for estimating peak discharges (Thompson, 2006; Willems, 2000). Figure 2 shows how to determine the time of concentration focusing at the peak discharge when a constant rainfall is applied.

For ease of use, rainfall duration will be referred as aggregation time in the following chapters of this document.

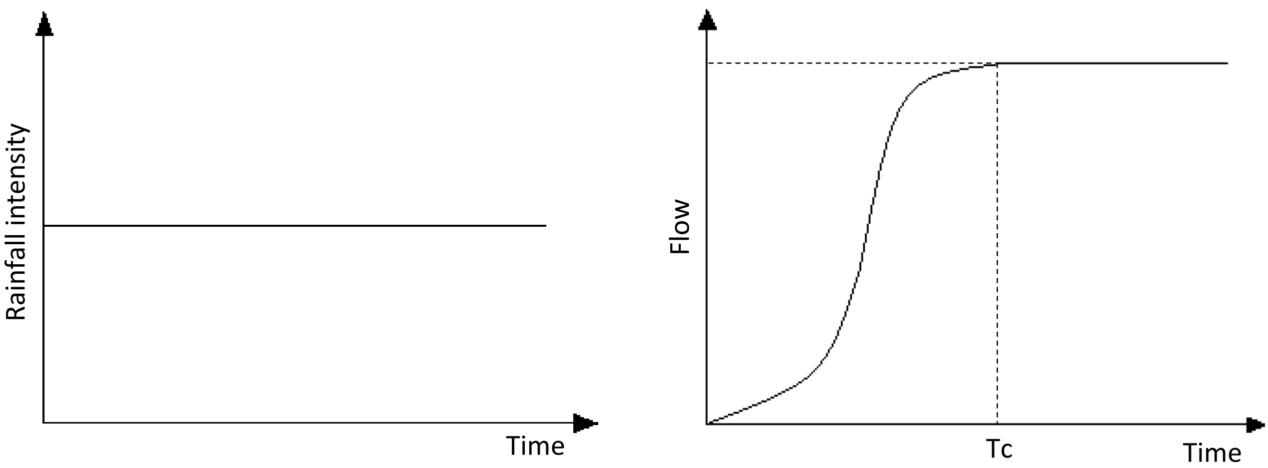


Figure 2: Time of concentration estimation by using the rational method.

4. Data and method

4.1 Lystrup catchment

In order to meet the specific objectives in this study, Lystrup catchment has been selected. Lystrup, is an urban area located in Jutland, Denmark, with 10.378 inhabitants (Danmarks statistics, 2015). The city is in the region of Midtjylland, and it is close to Aarhus. It has been chosen since there have been several recorded floods in recent years. The catchment has an overall slope direction from NW to SE. This affects the water dynamics leading to surface runoff and water accumulation in specific zones such as ponds. Figure 3 shows the location and delimitation of Lystrup catchment as well as its topography. The altitude in the NW is about 70 meters and it goes down to the SE up to 2 meters above the sea level. Two streams and a highway surround the city.

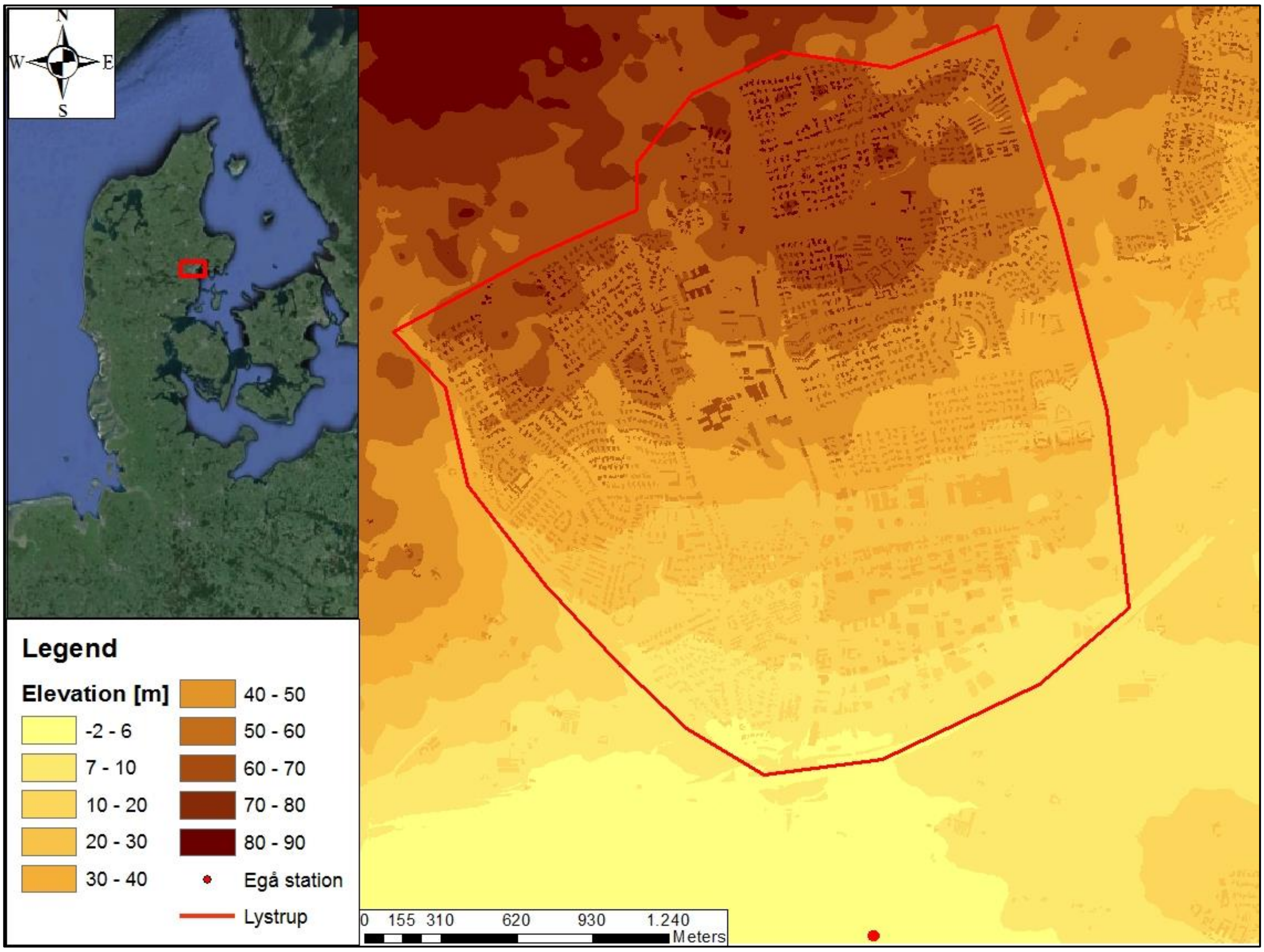


Figure 3: Location of Lystrup catchment in Denmark with a zoom of the catchment showing its topography and Egå rain gauge station.

The drainage system of Lystrup is a separate system consisting in two different types of pipes, collecting sanitary water and storm water separately. As mentioned, the design standards for separate drainage systems have to protect floods for a return period of 5 years (Spildevandskomiteen, 2005).

However, Lystrup was affected by major floods on 26 August 2012. A rainfall of 52 mm lasted for 5 hours and the drainage system exceeded its capacity leading to water surcharge onto several areas of the catchment.

After the extreme event of August 2012, 12 adaptation projects have been developed to prevent new flooding in Lystrup by setting up new storage basins, dams or changing roads and green areas (Aarhus Kommune, 2014). Table 1 shows some characteristics of the catchment.

Table 1: General characteristics of Lystrup catchment.

Lystrup catchment		
Total area	[ha]	438,6
Catchment length	[m]	2970
Catchment width	[m]	2700
Slope	[m/m]	0,021
Type of drainage system	[-]	Separate
Imperviousness[1]	[%]	40,1

1: total impervious areas in proportion to total area

4.2 Rainfall data

Two types of rainfall data are used for the analysis; synthetic and historical data.

Synthetic data is generally used when certain conditions have to be fulfilled and they cannot be achieved with historical data. As mentioned, these type of data, named Chicago Design Storm (CDS), is based on the Intensity, Duration and Frequency (IDF) curves, which are usually used to assess peak discharges for a given return period. They are built using rainfall observations and require less computational time. However, using these data for flood simulations might overestimate flood depths and extent significantly, because it is unlikely that the return period of the synthetic rainfall will have the same return period of flood extent and flood depth of the catchment (Thorndahl, 2015). In this study, synthetic data has been used as a constant rainfall to estimate the time of concentration of the system, under study. Two types of constant rainfall have been applied, one of 1 µm/s and another of 13 µm/s that lasts for 8 hours (Figure 4). Results of the obtained concentration times are explained in section 5.2.

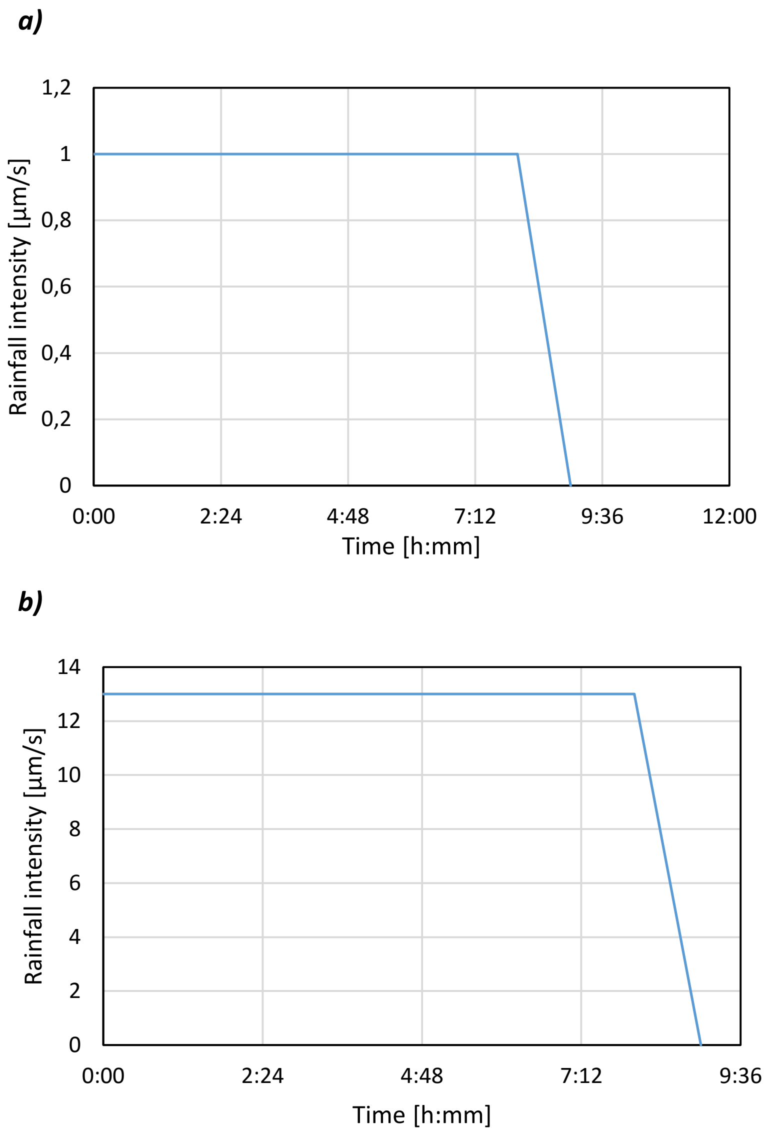


Figure 4: Synthetic rain series of a) 1 µm/s and b) 13 µm/s applied in this study.

Following the recommendations of Thorndahl (2015), a series of historical rainfall events have been used for modelling the complex urban drainage system under study.

Historical data contain measured rain for a particular time period, including dry periods. Tipping bucket rain gauges are a standard instrument for measurement of rainfall, which measure the volume over a certain period of time, which can be then converted to rainfall intensity in mm/h or µm/s (Davies, 2004). However, large amounts of data are often produced from recording from rain gauges.

A rain gauge network from the Danish Waste Water Committee is used to measure rainfall in Denmark with approximately 145 rain gauges distributed in all the country. The Danish Meteorological Institute (DMI) and the Engineering Society of Danish Wastewater Committee are responsible for all the data collection from the rain gauge network. All measurements pass both a manual and an automatic quality control where each meter is inspected and calibrated every two years (DMI, 2016).

A 27 years historical data set (Figure 5) of a rain gauge station located in Egå, SE Lystrup, is the historical rainfall input. The location of the station can be found in Figure 3.

In addition, the Waste Water Committee together with DTU has provided a tool called Rain Analyst allowing the statistical assessment of rain data sets. The tool provides return periods and maximum intensities for different aggregation times. The obtained statistics will be further used in this study to assess the return period of flood.

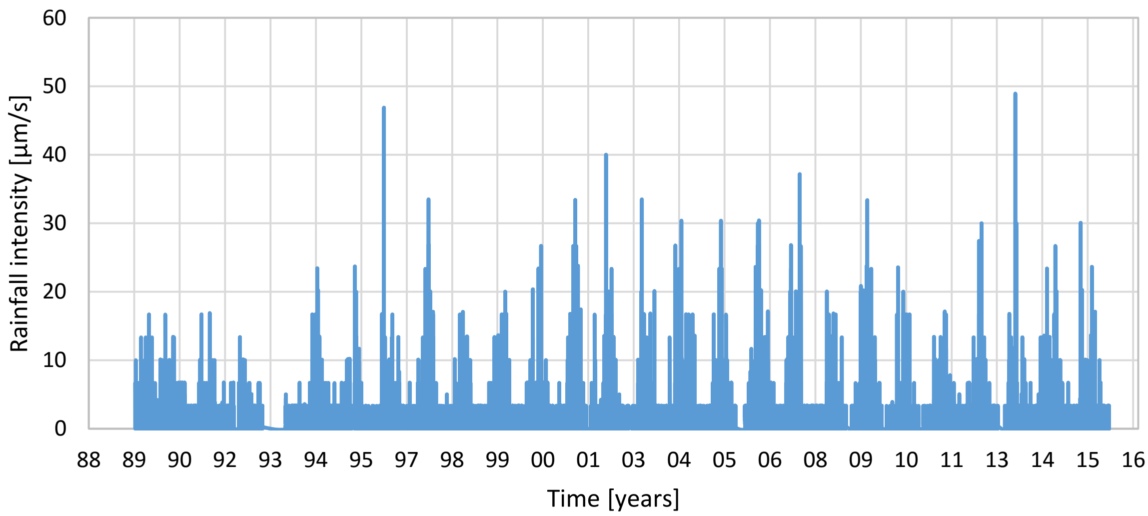


Figure 5. Historical rain series applied in this study from 1989 until 2016 (1 minute and event-based) from Egå rain gauge.

4.3 Urban flood model

Mike flood is the hydrodynamic model used in this study, which allows to simulate the largest flood events of Lystrup catchment. It consists in Mike Urban, 1D urban drainage, model which solves Saint-Venant equations and it is coupled to Mike 21, 2D surface model, which solves shallow water equations. Mike Urban is able to model an urban drainage system by combining a hydraulic pipe model and hydrological model based on Mouse engine. This tool integrates a GIS system that allows to upload a Digital Elevation Model (DEM), which in that case is specified as a raster data set containing elevation data of the terrain and allows to model surface water throughout the catchment (DHI, 2014).

Lystrup urban drainage model is the model used for this study and is provided by Aarhus Water and Orbicon, where the physical details of the system have been set. The model has been calibrated by Jepsen (2015) and

Thorndahl et al. (2016) by using as rain input the rain events of 26 August 2012 and 13-14 July 2014, which are the most extreme events from August of 1989 to February of 2016. However, it should be noted that this catchment has undergone several changes over the last 27 years in the drainage system and the terrain, which means that some of the results may be overestimated. At any case, this will not affect the objective set in this study since it aims to consider differences between rainfall and floods.

In addition, the model is simplified, meaning that some variables are not considered such as the soil moisture conditions.

4.3.1 Rainfall-runoff model

As mentioned, **MOUSE model** is built from two different sub-models: the hydrological surface model and the hydraulic pipe flow model (Thorndahl, 2008). Rainfall-runoff modelling is a method used to derive surface storm runoff and imperviousness on urban and semi-rural catchments (DHI, 2014). In order to set up a hydrological model, the Time-Area method is used to produce a flow hydrograph for each sub-catchment. It requires minimum data and allows to use time-varying rainfall (UNESCO-IHE, 2016). This method uses time-area curves which represent the contributing percentage of a catchment surface versus the time (DHI, 2014). Hydraulic network modelling contain the hydraulic elements such as nodes, links, basins outlets and weirs that will define the geometry and the dimensions of the drainage system (Jepsen, 2015).

The main characteristics of the network system are listed in Table 2 and illustrated in Figure 6 showing details of the number of elements that define the network system or the total effective area, which is calculated taking into account the reduction factor and the impervious area for each of the sub-catchments. The imperviousness of the system is between 25 and 50 % in the residential areas located in the west and the north of Lystrup, whereas between 50 and 75% in the SE of the area, where the industrial area is found (Jepsen, 2015).

Table 2: Main hydraulic elements of the Lystrup model.

Lystrup model		
Nº Nodes		1526
Nº Outlets		21
Nº Basins		25
Nº Pipes		1550
Nº Weirs		33
Nº sub-catchments		1455
Reduction factor	[-]	0,9
Total effective area	[ha]	160,94

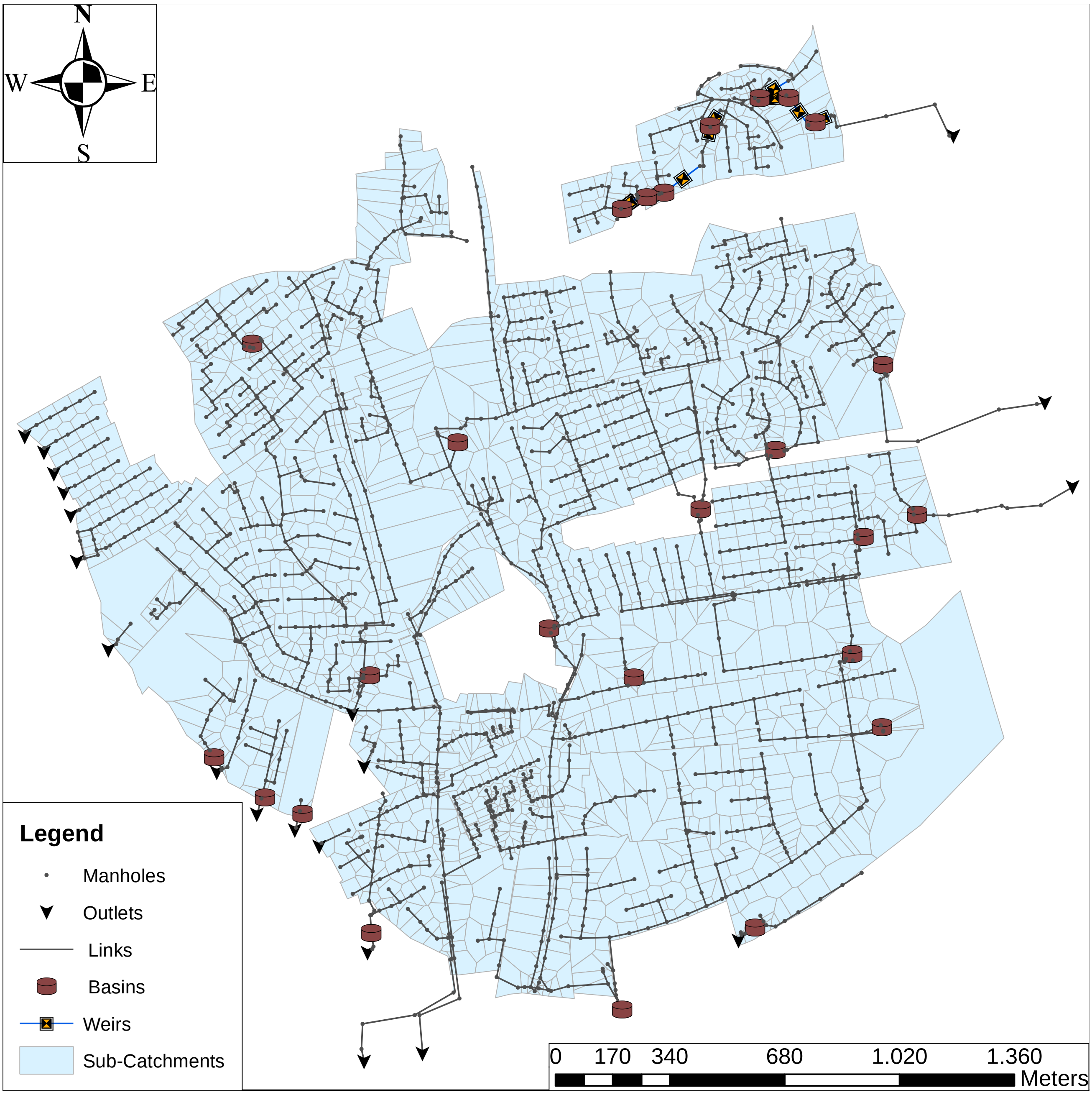


Figure 6: Map of the main hydraulic elements of the Lystrup model.

4.3.2 2D overland flood model

In order to delineate the 2D model area, a raster DEM layer of 2x2m resolution is used, where the catchment area is digitized with a single grid cell of a size of the same cell of 2 m equal to the DEM (Jepsen, 2015).

Some of the 2D model settings that are specified by default are the drying and flooding depth, which reduce the simulation time by not simulating the flow in the dry cells and considering flood as from a certain depth. These criteria are 0,002 m for drying depth and 0,003 m for flooding depth, thus below 0,002 m no surface flooding is considered (DHI, 2014).

The maximum flood extent and flood volume used in this study are defined as follows:

- Max. flood extent: *'Number of flooding grid cells'* x *'grid spacing (2x2m)'*
- Max. flood volume[1]: *'Sum of all maximum water level'* x *'grid spacing (2x2m)'*

[1]: For water levels > 0,002 m

4.3.3 Connection between 1D-2D models

In order to simulate the rainfall-runoff, the system under study is divided in sub-catchments. For each of them, a rainfall input is applied and connected to the drainage system through the manholes. First, runoff is estimated based on the rainfall and sub-catchment characteristics. After that, the remaining amount of water is given as input for the drainage system. Besides, the network nodes are connected with the 2D overland mesh, so the nodes are connected in both the sub-catchments and the 2D overland surface. When the urban drainage system capacity is surcharged, the exceedance water flows to the overland surface (Pina, 2016).

4.4 Extreme rainfall event selection

The data input consists of a 27 years rainfall historical dataset from Egå rain gauge. The entire dataset is considered for runoff simulation, where from its results a selection of the most extreme events is done.

Long term statistics (LTS) is a function in Mike Urban which allows to simulate continuous hydrological inputs covering long historical periods. It can convert a long term simulations into a discontinuous series considering only the relevant periods based on a specific criteria. In this study, LTS is used to select the largest and most extreme events of the 27 years historical data.

The selection of the largest events that will be simulated by the hydrodynamic model is based on a threshold which limits the total inflow entering to a catchment. The criteria is set to 15 m^3/s, which generates a total of 21 events selected from the total 27 years data set.
The next step in the extreme rainfall relation is the network simulation of the 21 preselected events (without 2D overland simulation) whose focus will be set on the number of manholes surcharged. Table A.1 of Appendix shows the 21 preselected events and their total number of surcharged nodes for each event.

The last step on the selection process is done throughout the platform Mike View, where the number of surcharging manholes are used for selecting the highest 10 events (Table 3). This final selection is used to run the network +2D overland model, which is a function in Mike Urban that corresponds to the Mike flood.

The selected events range from 1996 to 2016 with a duration range from 322 minutes on 26 August 2012 to 28 minutes, on 8 June 1996. For each event, a summary of the main characteristics is given, such as the total rainfall depth (mm) and the average rainfall intensity (mm/h). There are some events that last for short time but have higher intensity, while other events last for longer time but with lower rainfall intensity, thus different types of rainfall are considered for the 2D surface flood modelling.

Table 3: Summary characteristics of the selected extreme rainfall events

Events	Start	End	Duration	Number nodes surcharged	Total rainfall depth	Average rainfall intensity	Rainfall intensity 10 min	Rainfall intensity 30 min	Rainfall intensity 60 min	Rainfall intensity 180 min
[-]	**[hh:mm]**	**[hh:mm]**	**[min]**	**[-]**	**[mm]**	**[µm/s]**	**[µm/s]**	**[µm/s]**	**[µm/s]**	**[µm/s]**
08/06/1996	13:32	14:00	28	408	17	10,12	24,33	9,44	4,72	1,54
24/08/1997	12:47	13:27	40	173	19,2	8,00	18,33	8,33	5,33	1,78
12/08/2002	2:33	7:36	303	156	34,8	1,91	16,67	10,00	6,13	2,95
07/08/2005	17:11	20:16	185	172	33,2	2,99	17,67	9,11	6,22	3,07
01/08/2006	22:40	3:16	276	193	56,2	3,39	17,67	10,56	9,06	4,82
12/08/2006	12:37	13:29	52	220	21	6,73	19,33	10,44	5,83	1,94
25/06/2007	18:32	23:51	319	201	37,6	1,96	18,00	10,00	6,46	2,90
22/08/2012	1:29	4:30	181	118	25,2	2,32	15,00	8,33	5,74	2,33
26/08/2012	2:07	7:29	322	178	51,6	2,67	17,67	13,56	9,26	4,46
05/05/2015	14:25	14:25	51	250	17,2	5,62	20,67	9,17	4,78	1,59

5. Results and discussion

Results obtained from the 2D network simulation of the 10 events are presented and discussed throughout this section.

First, results showing the maximum flood volume and the maximum flood extent for the whole catchment in all the 10 events are shown in section 5.1. These results are compared with the statistics of historical rainfall.

In sections 5.2 and 5.3 based on the first results, 4 points from the catchment are selected to analyse the maximum water level of flood for all 10 events. These results are also compared with the statistics of historical rainfall, where the aggregation time of rainfall at each point is estimated by calculating the time of concentration for each of the selected study points.

Finally, at section 5.4, the maximum flood volume and maximum flood extent results are compared with the maximum flood level results.

5.1 Flood extent and flood volume for the whole catchment

In this section, the results from the maximum flood volume and maximum flood extent in each event are presented. First, the relation between the flood extent and flood volume is plotted, and then is compared with the statistics of rainfall. Figure 7 shows one of the major flooding events at 26 August 2012. Maximum flood level figures from the other 9 events are shown in Appendix B.

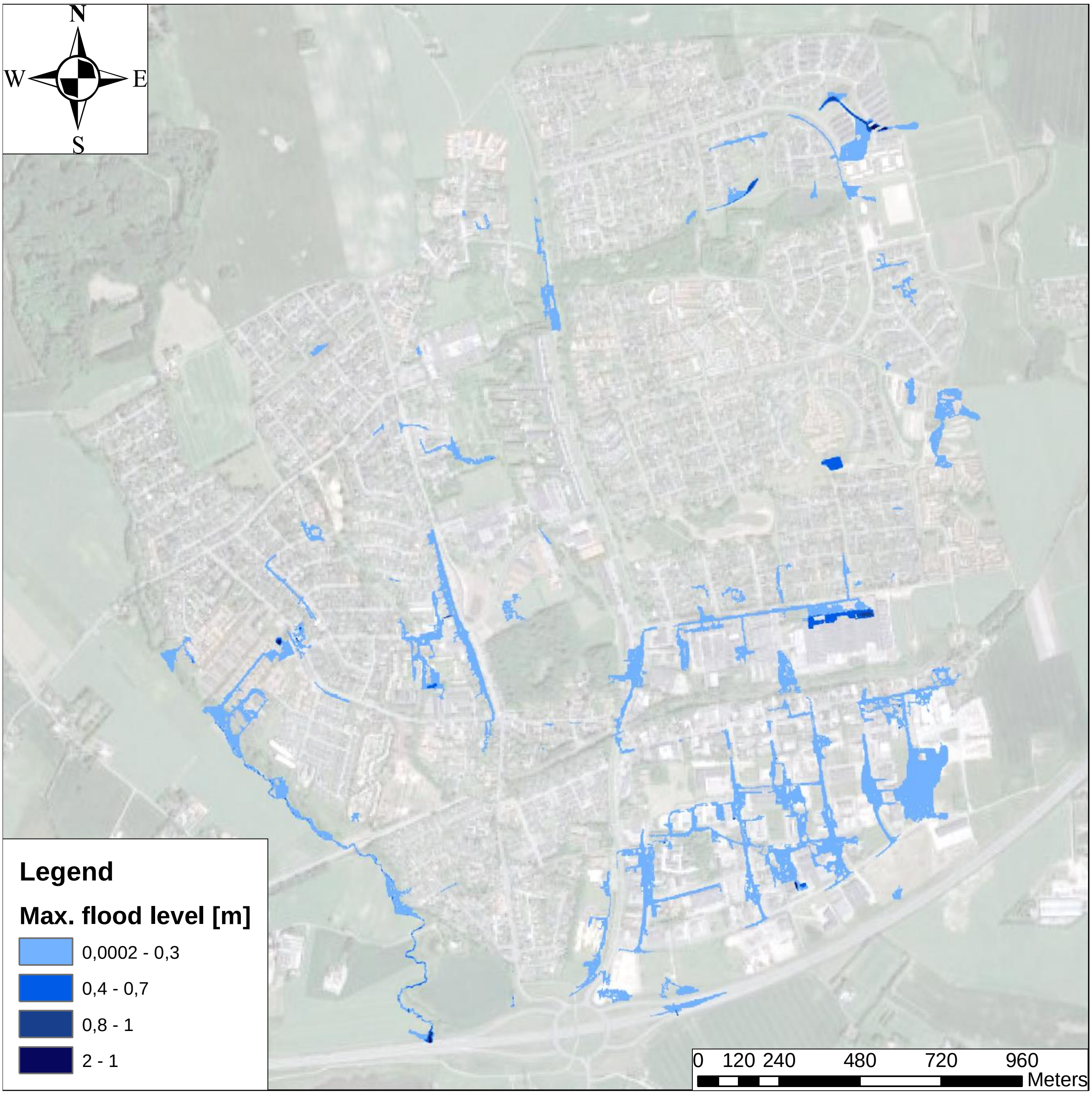


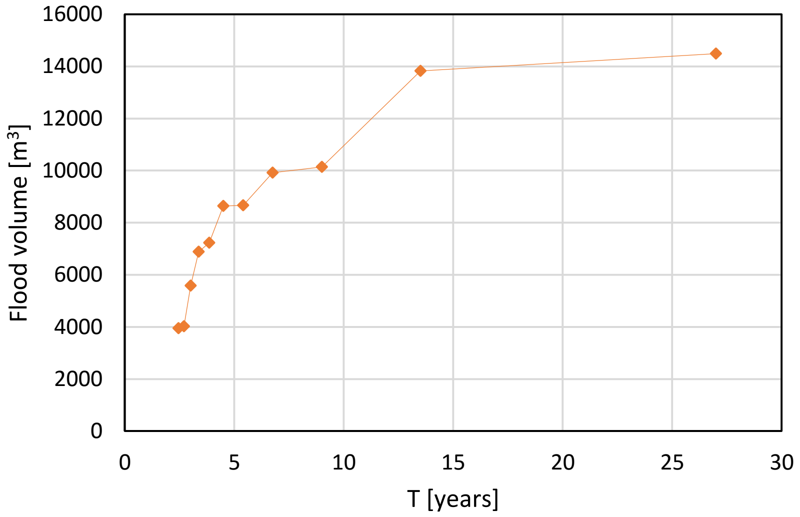
Figure 7: Maximum flood level on 26 August 2012.

Figure 8 shows the return period of maximum flood volume and maximum flood extent for each event, where the difference between them can be seen when both are plotted independently. As it can be seen at Figure 8a and Figures 8b and c, the highest flood event at Figure 8b is not the same event as the highest one in Figure 8c. These differences may be due to the dynamics of the surface flow since Lystrup catchment has a large terrain variability containing some flat and steep areas.

a)

Events	T [year]	Flood volume [m³]	Events	T [year]	Flood extent [m²]
26/08/2012	27,0	14484	08/06/1996	27,0	471772
01/08/2006	13,5	13821	05/05/2015	13,5	330132
25/06/2007	9,0	10134	01/08/2006	9,0	302208
08/06/1996	6,8	9914	12/08/2006	6,8	291720
12/08/2002	5,4	8670	25/06/2007	5,4	289668
07/08/2005	4,5	8644	26/08/2012	4,5	276788
05/05/2015	3,9	7223	07/08/2005	3,9	249052
12/08/2006	3,4	6883	12/08/2002	3,4	235356
22/08/2012	3,0	5582	24/08/1997	3,0	227400
24/08/1997	2,7	3949	22/08/2012	2,7	202500

b)



c)

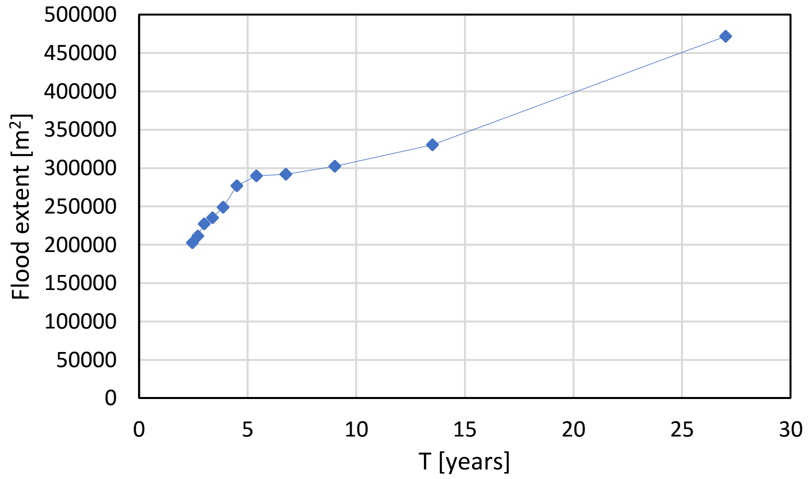
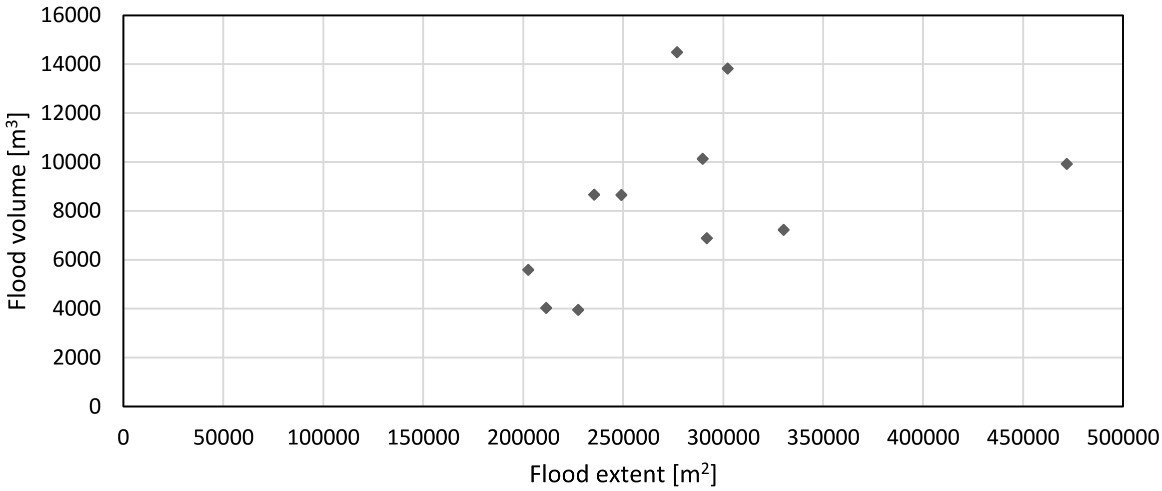


Figure 8: Figure *a)* shows the maximum flood volume, the maximum flood extent and their respective return period ranked for each of the 10 events. Figure *b)* shows the maximum flood volume versus the return period for the 10 events, whereas Figure *c)* shows the maximum flood extent versus the return period for the 10 events.

By plotting the maximum flood extent versus the maximum flood volume some differences are found (Figure 9). The correlation is weak (0,40) and it may be due to the catchment surface characteristics, where water acumulates in deep areas leading to flood. It can be seen that the scatter points are widely dispersed without following any linear behaviour. Moreover, the event with the highest flood volume does not correspond with the event with the highest flood extent. If there were a very good correlation the flood depth would be the same in the whole catchment, meaning that this weak correlation might also indicate large variability in flood depths locally. Values from Figure 9 can be found at Table A.2 in Appendix.

a)



b)

Coefficient of correlation	**0,40**

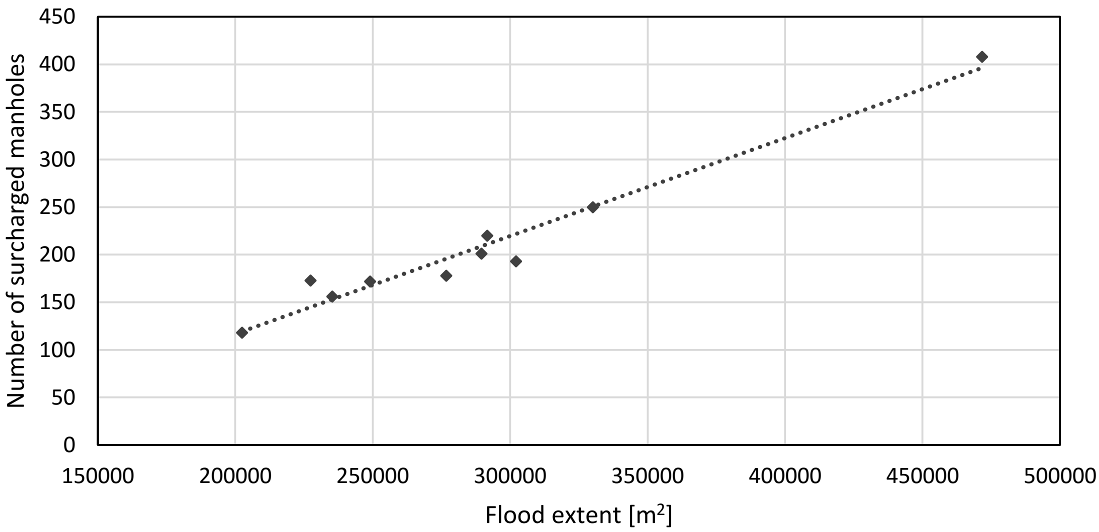
Figure 9: *a)* Maximum flood volume versus maximum flood extent for the 10 events at the whole catchment. *b)* Coefficient of correlation between flood extent and flood volume.

When the maximum flood extent and the number of surcharged manholes are plotted a very good correlation is found (Figure 10). Thus, as the number of surcharged manholes increases, more water will be in the catchment and larger the flood extent will be.

a)

Events	Flood extent [m²]	Nº Surcharged manholes
08/06/1996	471772	408
05/05/2015	330132	250
01/08/2006	302208	193
12/08/2006	291720	220
25/06/2007	289668	201
26/08/2012	276788	178
07/08/2005	249052	172
12/08/2002	235356	156
24/08/1997	227400	173
22/08/2012	202500	118

b)



c)

Coefficient of correlation	**0,98**

Figure 10: Maximum flood extent ranked versus total number of surcharged manholes for the 10 events. c) shows its coefficient of correlation.

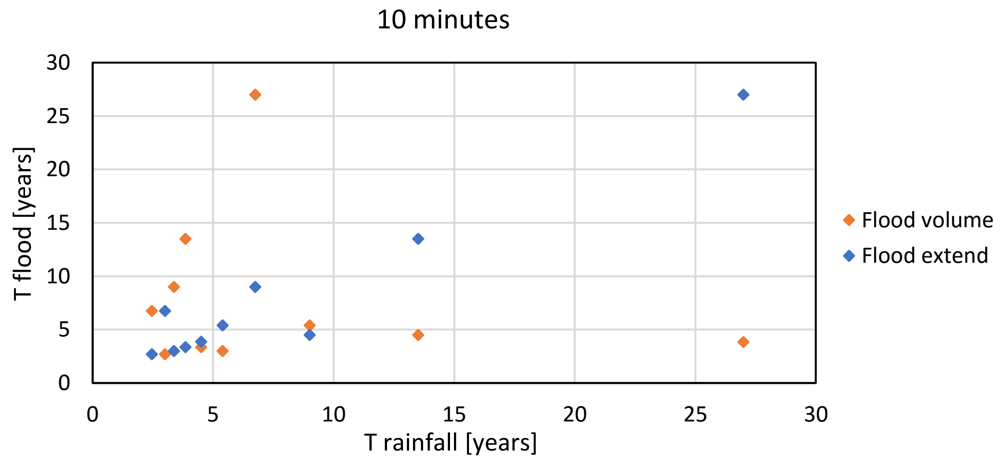
5.1.1 Comparison with rainfall statistics

Return period of flood volume and flood extent is compared with the return period of the rainfall. In Figure 11 this comparison is shown for aggregation times of 10, 30 and 60 minutes for the 10 selected events.

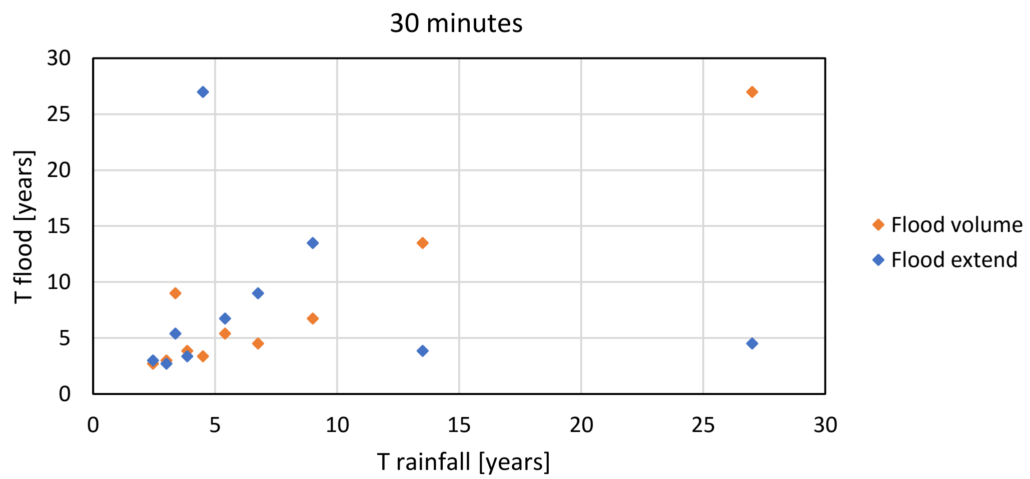
For 10 minutes results show disperse points and weak correlation when the return period of flood volume versus the return period of rainfall are plotted, whereas when the return period of extent is plotted instead, the points are following a positive slope. For aggregations of 30 and 60 minutes the coefficient of correlation of return period of flood volume and rainfall is higher than for 10 min, following positive slope. However, for the return period of flood extent versus the rainfall for 30 and 60 minutes the scatter points are very disperse.

Differences between different aggregation times may be due the fact that for aggregations of 10 minutes, water has not had time to contribute in all the catchment probably due to the fact that concentration time is larger than 10 minutes. Nevertheless, for aggregations of 30 and 60 minutes of rainfall the correlation with flood volume is higher since all water that contributes is being stored in urban areas. The results also show that is not necessarily the same rainfall aggregation time in the whole catchment because the time of concentration might not be the same in the whole catchment. Specific values from Figure 11 can be found at Table A.3 and A.4 in Appendix.

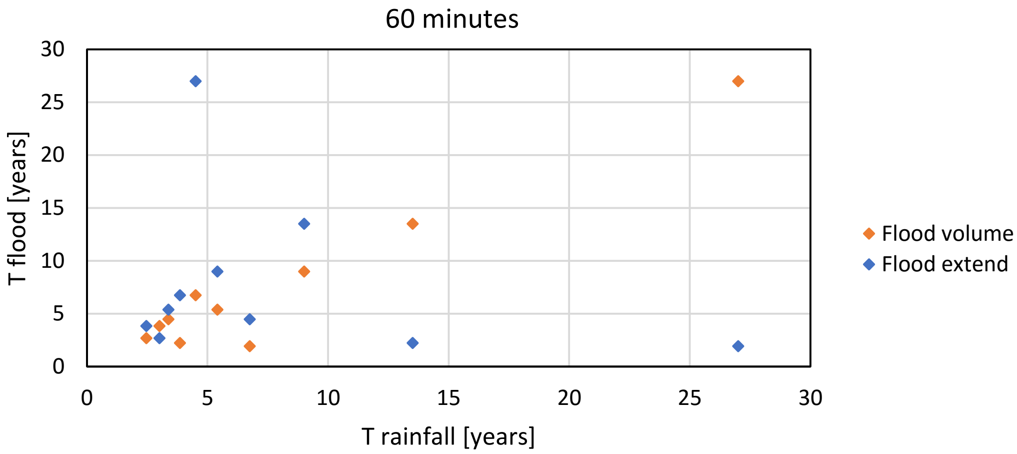
a)



b)



c)



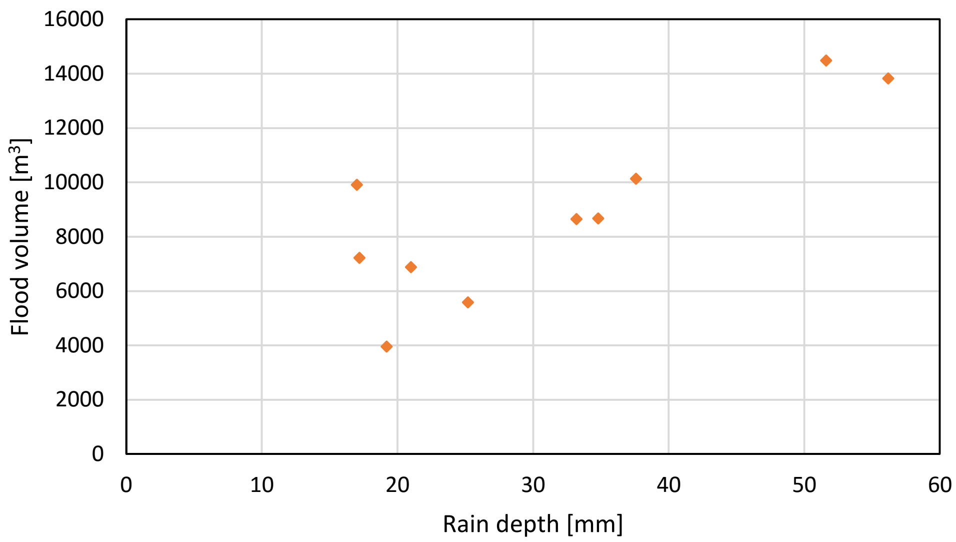
d)

Coefficient of correlation			
	T rainfall		
	10 min	***30 min***	***60 min***
T flood volume	-0,18	0,96	0,97
T flood extent	0,96	-0,12	-0,27

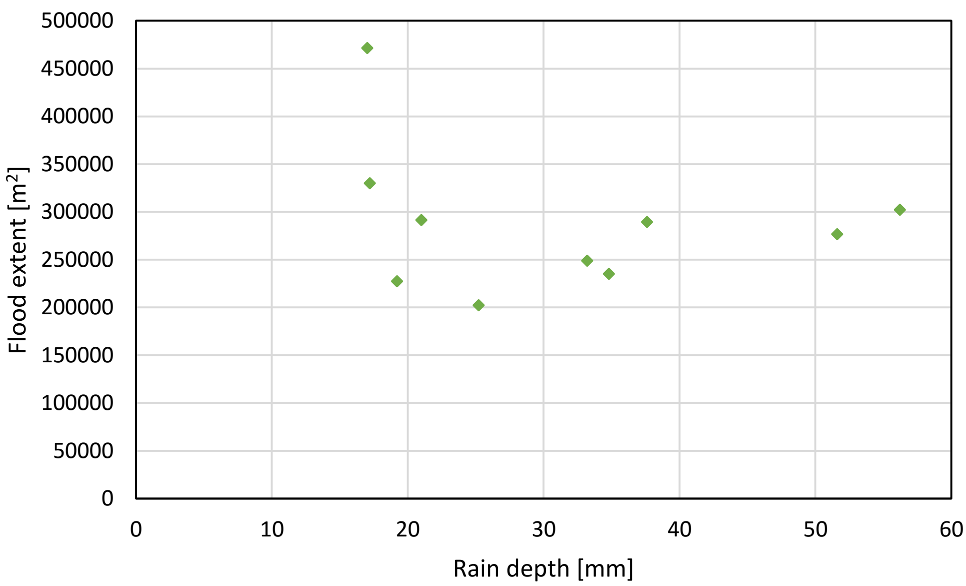
Figure 11: Return period of flood versus return period of rainfall intensity for 10, 30 and 60 minutes.

A comparison is made with the flood extent and flood volume values in regards to rainfall depth (in mm). Figure 12 (a, b and c) shows the correlation between flood volume and rain depth (Fig. 12a), which is much better than the correlation obtained between flood extent and rain depth (Fig. 12b). As seen in figures 12b and c, the correlation between the flood extent and the rain depth is negative, meaning that for very low rain depth the flood extent can vary a lot. Thus, even during extreme events, the flood extent can still be small. However, it can be also observed that for higher rain depths, a higher correlation is found, whereas several low rainfall depths lead to higher dispersion on the consequent flood extents. Values from Figure 12 can be found at Table A.5 and A.6 in Appendix.

a)



b)



c)

	Flood volume	**Flood extent**
Coefficient of correlation	0,83	-0,22

Figure 12: *a)* Maximum flood volume versus rain depth and *b)* Maximum flood extent versus rain depth for the 10 selected events. *c)* Coefficient of correlation of flood volume versus rain depth and flood extent versus rain depth.

Discussion

Some of the outcomes found in that section are:

- The event with the highest return period of maximum flood extent is not the same event with the highest return period of maximum flood volume.
- The correlation between maximum flood extent and maximum flood volume is weak, which might indicate large variability in flood depths locally.
- Good correlation between number of surcharged manholes and maximum flood extent
- For aggregation times of 30 and 60 minutes, the return period of flood volume versus rainfall is better correlated than the return period of flood extent versus rainfall.
- The aggregation time is not necessarily the same in the whole catchment, so the time of concentration might also be different.
- The correlation between the maximum flood volume and rain depth presents better results in comparison with the correlation between the maximum flood extent and rain depth, which is negative.

5.2 Analysis of local flooding

In order to study the most vulnerable areas in the catchment regarding to surface flood, 4 points have been selected and analysed in detail considering characteristics such as the contribution area and slope. After that, the time of concentration is assessing at different parts of the catchment and considered as well. The distance between the selected study points and the nearest surcharged manhole is given and considered as well.

The criteria to choose these 4 points is based on the presence of flooding after the simulation of the 10 selected events. Figure 13 shows the 4 points selected and their contribution areas. The coordinates of the points can be found at Table A.7 in the Appendix. A description of each selected point is presented in this section and Table 4 contains the important details from each point. The time of concentration for each point is also calculated and their results are presented at the end of this section.

Figure 13: Selected study points and their corresponding contribution areas.

Point A

The area that involves point A has a small and independent network system with some basins and is located in the north part of the catchment as shown Figure 13. Point A is close to a manhole which has been flooded during the selected 10 events and most of the flooded area around the point is coming from that manhole. Figure 14 shows a detail of the point, the surcharged manhole and the flood extent from the event on 26 August 2012. It is located in a flat area and surrounded by 4 basins, which do not directly affect to the study point. The contribution area in that point is small, around 0,5 ha since point A is located close to upstream manhole of the drainage system. The contribution area corresponds to the sub-catchment area where point A is located.

Figure 14: Location of point A showing the maximum flood level from the 26 August 2012, the contour lines of surface elevation and the ground level from the surcharged manhole.

Point B

Point B is located in a bigger system at the western part of the catchment (see Figure 13) and about 30 meters distance from the nearest surcharged manhole, which has been flooded during all the 10 selected events. Figure 15 shows the point and the flooded area around that belongs to the event on 26 August 2012. Water at point B flows from several manholes located close to the study point, which due to the high slope water runs over the surface and tends to accumulate at the selected point. In that case, most of the water flows to that point which mainly proceed from surface flood water rather than the network, so for point A no storage basins are affecting the point. The contribution area is around 2,4 ha, thus there is a larger amount of sub-catchments that contribute to surface flooding.

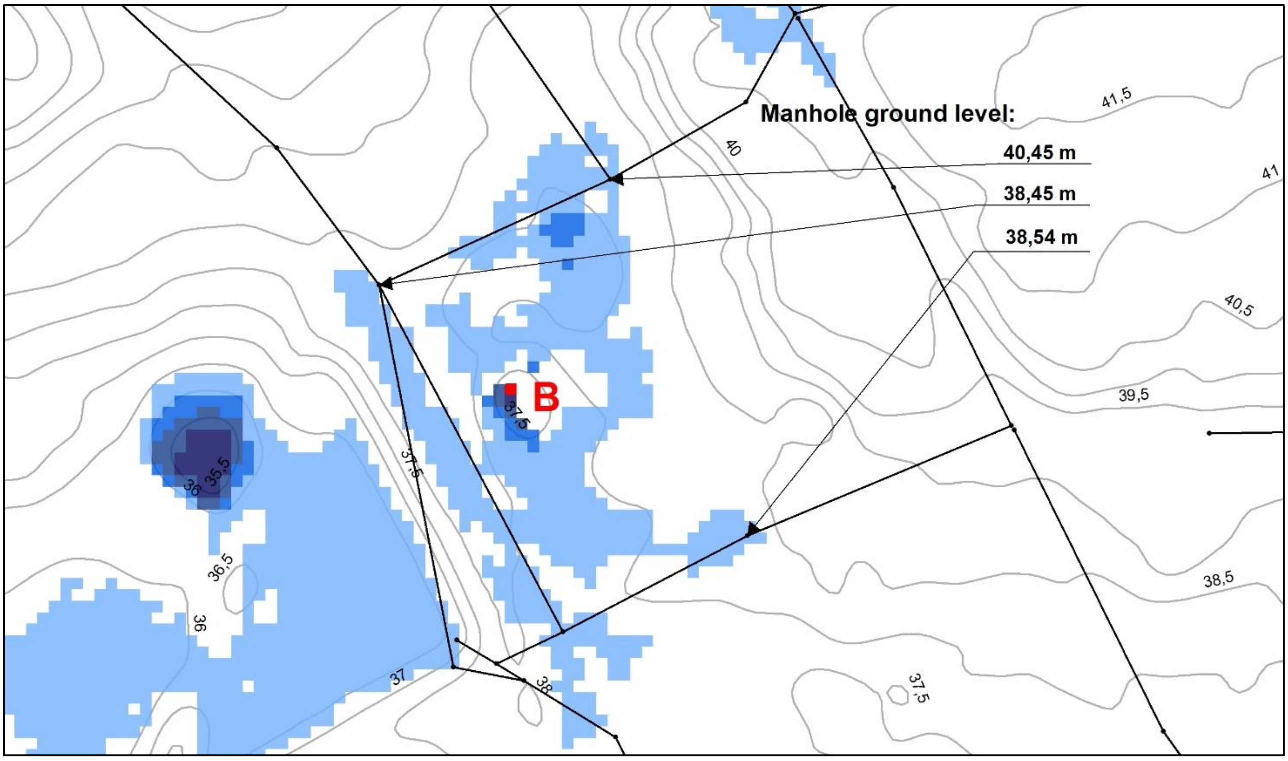


Figure 15: Location of point B showing the maximum flood level from the 26 August 2012, the contour lines of surface elevation and the ground level from the surcharged manholes.

Point C

Point C is located in the eastern part of the system (seen in Figure 13). The selected point is located in a critical zone which has recorded flooding for all the selected events and it is about 50 meters far from the nearest surcharged manhole (Figure 16). It is a steep area, so the contribution of surface water is coming from several surrounding manholes, which are located upstream of the sub-system. In addition, no basins are found around the selected point. Since point C is located upstream of the system, the contribution area is small, around 0,23 ha.

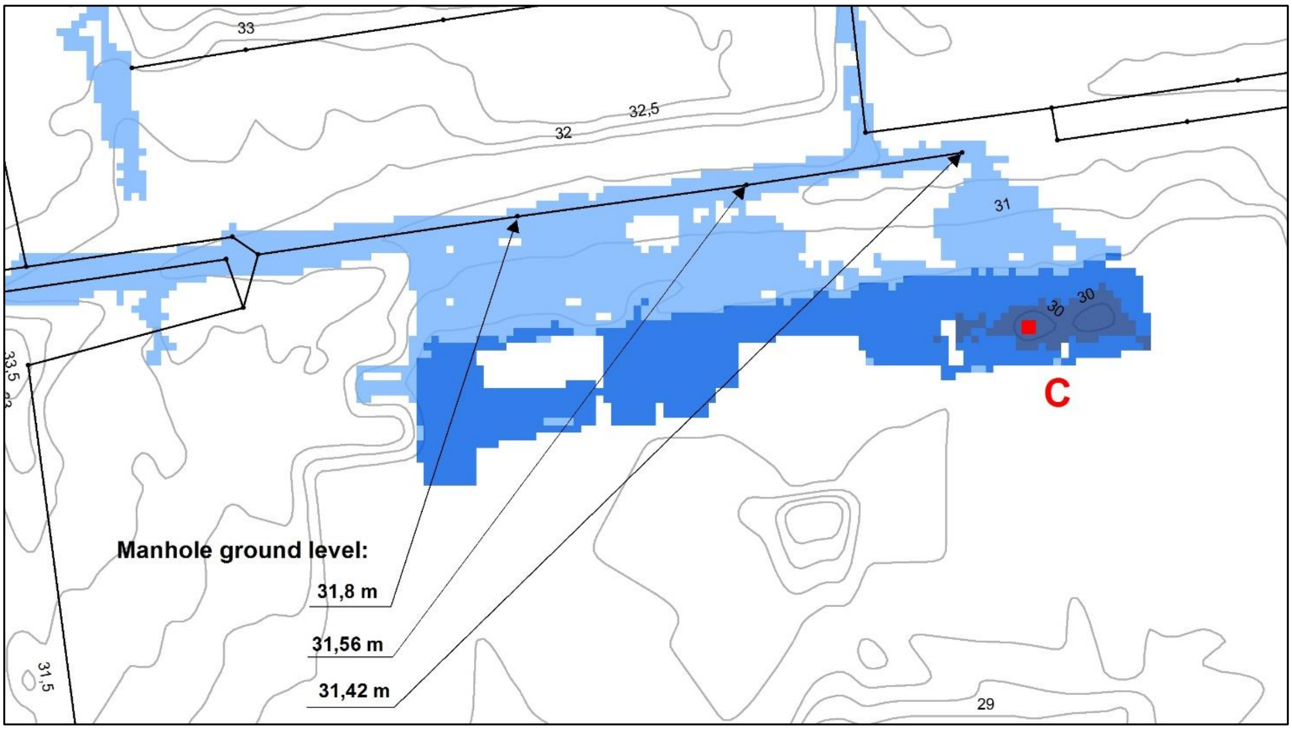


Figure 16: Location of point C showing the maximum flood level from the 26 August 2012, the contour lines of surface elevation and the ground level from the surcharged manholes.

Point D

Point D is located in the south of the system (see Figure 13), and flood has been recorded in 5 of the 10 selected events. The point is located far from the surcharged manholes and in that case, when flooding occurs, water is coming from a stream. Thus, point D receives more influence by surface flooding than network surcharged water. In the upstream area, there is a sub-system, which has seen water surcharged from several manholes. This water is flowing by gravity through the stream, until it reaches a more flat area where it is accumulated. Figure 17 illustrates the surrounding area, the location of point D and the surcharged manholes. The contribution area is 7,06 ha, the biggest of all the selected points due to different sub-systems involved.

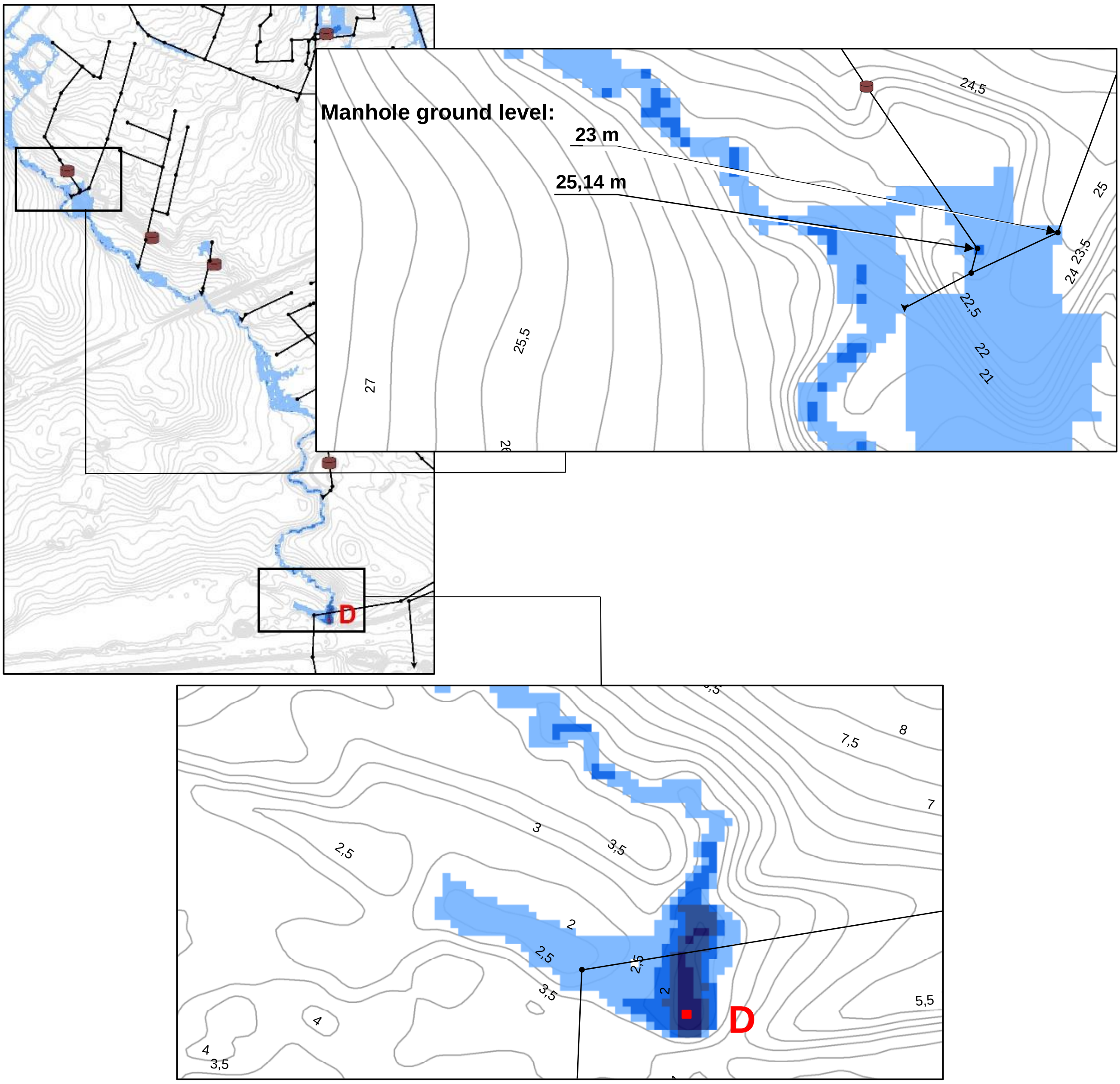


Figure 17: Location of point D showing the maximum flood level from the 26 August 2012, the contour lines of surface elevation and the ground level from the surcharged manholes.

Table 4: Topographic and network features for each point

Point	Contribution area	Mean slope[2]	Slope terrain contr. area[3]	Slope terrain from near manhole[2]	Distance to near manhole	Nº of connected nodes
[-]	[ha]	[m/m]	[m/m]	[m/m]	[m]	[-]
A	0,05[1]	0[1]	0,0064	0,0072	3,5	0[1]
B	2,44	0,024	0,0148	0,051	30	36
C	0,23[1]	0[1]	0,0362	0,036	50	0[1]
D	7,06	0,015	0,0198	0,0217	1140	81

1: Beginning of a network system

2: Mean slope of the pipes from the network system of the contribution area

3: Slope of the terrain in the contribution area

4: Slope of the terrain from the nearest surcharged manhole until the selected point

5.2.1 Time of concentration at Lystrup catchment

The time of concentration is needed in this study in order to estimate the aggregation time of the contributing catchment for each of the selected points. According to the rational method (Thompson, 2006), the aggregation time of an event has to be equal to the time of concentration for estimating peak discharges. In this study two different types of time of concentration are considered.

The first one (T_n), is the network concentration time, which includes the catchment concentration time. The catchment concentration time is the time that water needs to flow over the catchment until it reaches the drainage system. It is obtained directly from the model, which is set as a default, and has a value of 7 minutes constant for all sub-catchments.

The second one (T_s), is the time of concentration of the surface flood from the network to selected point. When manholes are surcharged, because the network system exceeds its capacity, water flows out of the system. The time of concentration of the surface flood is the time that water needs to flow from the network until it reaches the selected point. Thus, the total time of concentration set in this study is:

$$T_c = T_n + T_s$$

The time of concentration for both the water in the network and water on the surface has been estimated for each point.

If an historical event is used to estimate the time of concentration, it would cause some disturbances due to the dynamics of the rainfall varies from event to event. Thus, a constant rain has been applied since the aggregation time has to last at least the same time as the time of concentration. In order to find the network time of concentration (T_n) a constant rainfall of 1 µm/s is applied. In this way, disturbances of rainfall are minimized. On the other hand, a constant rainfall of 13 µm/s is used to estimate the surface time of concentration (T_s). This intensity is chosen to assure that flood is generated onto the study points. Figure 4 in section 4.2 shows the rainfalls applied to estimate both times of concentration.

Tn from network system

When the constant rain of 1 µm/s is applied, the aggregation time and the time of concentration are the same, so the maximum flow is reached when all water from the sub-catchments is contributing.

A runoff and network simulation is run in Mike urban with rainfall input of 1 µm/s during 8 hours. Since 1 µm/s can be considered as a low value, the initial loss is set to 0 meters. In order to get the concentration time at the breakthrough curve, the discharge of the closest pipe to the study point has to be looked. By considering the smaller event of 1 µm/s, it ensures that all the water is been discharged, so preventing water to accumulate at storage basins. It is a constant event of 8 hours long so it assures that water flows through the whole system. The time of concentration is estimated considering the beginning of the discharge until the end of the breakthrough curve, when it becomes constant. This time of concentration can be longer if any storage basins are located within the sub-system. Figure 18 shows the discharge at point A and as it can be seen it takes around 11 minutes to become constant. Results can be found at Table 5.

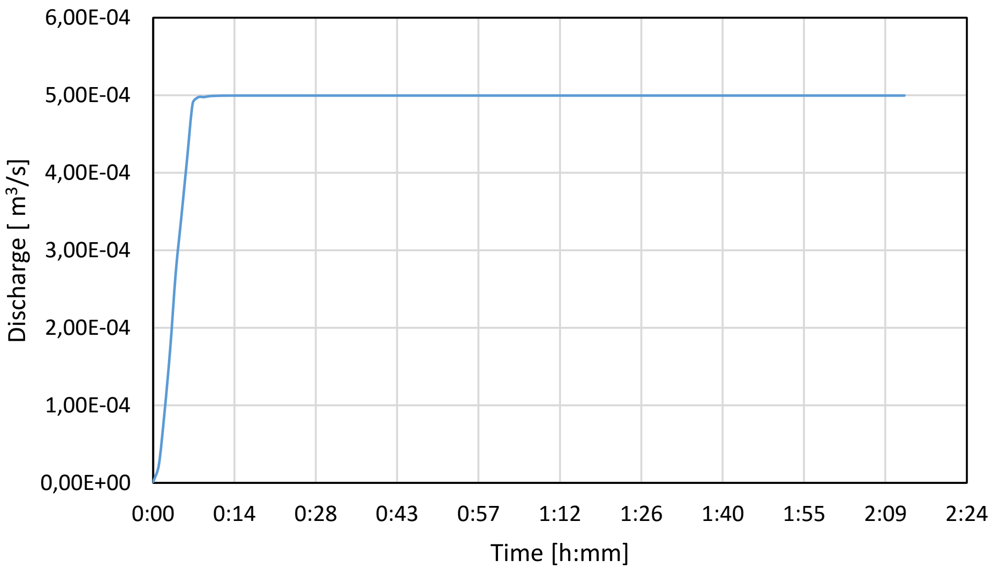


Figure 18: Discharge from point A for the first 2 hours.

Ts from surface inundation

The surface time of concentration (T_s) is estimated by analysing the main paths that flood water follows, thus, noting the time when water starts to surcharge from the nearest manhole until it reaches the considered point. In that case, a constant rainfall of 13 µm/s is applied and results are presented in Table 5.

Table 5: Time of concentration of the network system and surface flood for each of the points.

	Time of concentration		
Point [-]	**Network** [min]	**Surface** [min]	**Network + surface** [min]
A	11	1	12
B	28	10	38
C	12	11	23
D	60	81	141

Table 5 shows the time of concentration estimated from the network and the surface runoff, and also the total time of concentration for each selected point.

The time of concentration of the network at points A and C is calculated at beginning of the, so their results are very similar. This is mainly happening because their contribution area is smaller than other points and they are not affected by basins and other upstream manholes. The time of concentration of the network at point B is higher than A and C because the contribution area is larger in B, so a large amount of nodes is involved. As said at the beginning of this section, there are no basins at this point which increases the accuracy of the estimated time of concentration. Time of concentration at point D is complex to estimate since it is influenced by surface water of a stream. However, from the value shown at Table 5, the Tc from is most influenced system upstream and the obtained Tc value is quite high due to it is affected by a basin as it is explained at the beginning of this section.

Concerning the results of the surface time of concentration for all the 4 points, they are comparable to each other in regard to their topographical features shown in Table 5. Areas B and C are more similar than A and D. At point A the distance from the nearest surcharged manhole to the point A is around 3,5 m, and the contribution area is nearly flat, with a slope of 0,0064 m/m. This explains the low value of 1 minute of Tc at point A. In addition, the estimated value also explains that most of the water comes from the manhole, so this point is more influenced by water coming from network.

Estimated surface time of concentration at points B and C is higher when compared to point A, due to slope characteristics and the distance from the nearest surcharged manhole, which for the point B is 30 meters and to point C, 50 meters. Their slopes are 0,0148 m/m and 0,0362 m/m for B and C respectively. Their surface time of concentration is very similar, 10 and 11 minutes respectively. Both points are more influenced by surface flood than network surcharging.

Regarding to point D, the distance between the nearest surcharged node to the point is more than 1 km and the slope of the contributing area is around 0,0198 m/m as shown in Table 5. The water flows throughout the stream and in consequence the time of concentration is much longer, more than 1 hour. So point D is also highly influenced by surface flood.

Discussion

Some of the outcomes found at that section are:

- Since it is an irregular catchment where the areas affected by floods are very different each other, the 4 chosen points have different characteristics each other, in regards to the network system and terrain.
- The chosen local points have different estimated time of concentration, stating again the basin is irregular.
- At some points, flooding is caused by water coming from multiple manholes

5.3 Maximum flood level at local flooding

In this section, results from the maximum flood level (max H) at the 4 local points are presented. First, the return period of the maximum flood level for the 4 points and for each event is plotted. Then, the aggregation time for each point is chosen and the return period of maximum flood level and the return period of the rainfall is done.

Figure 19 illustrates the maximum flood level on 26 August 2012 as well as the location of the 4 local points selected in section 5.2.

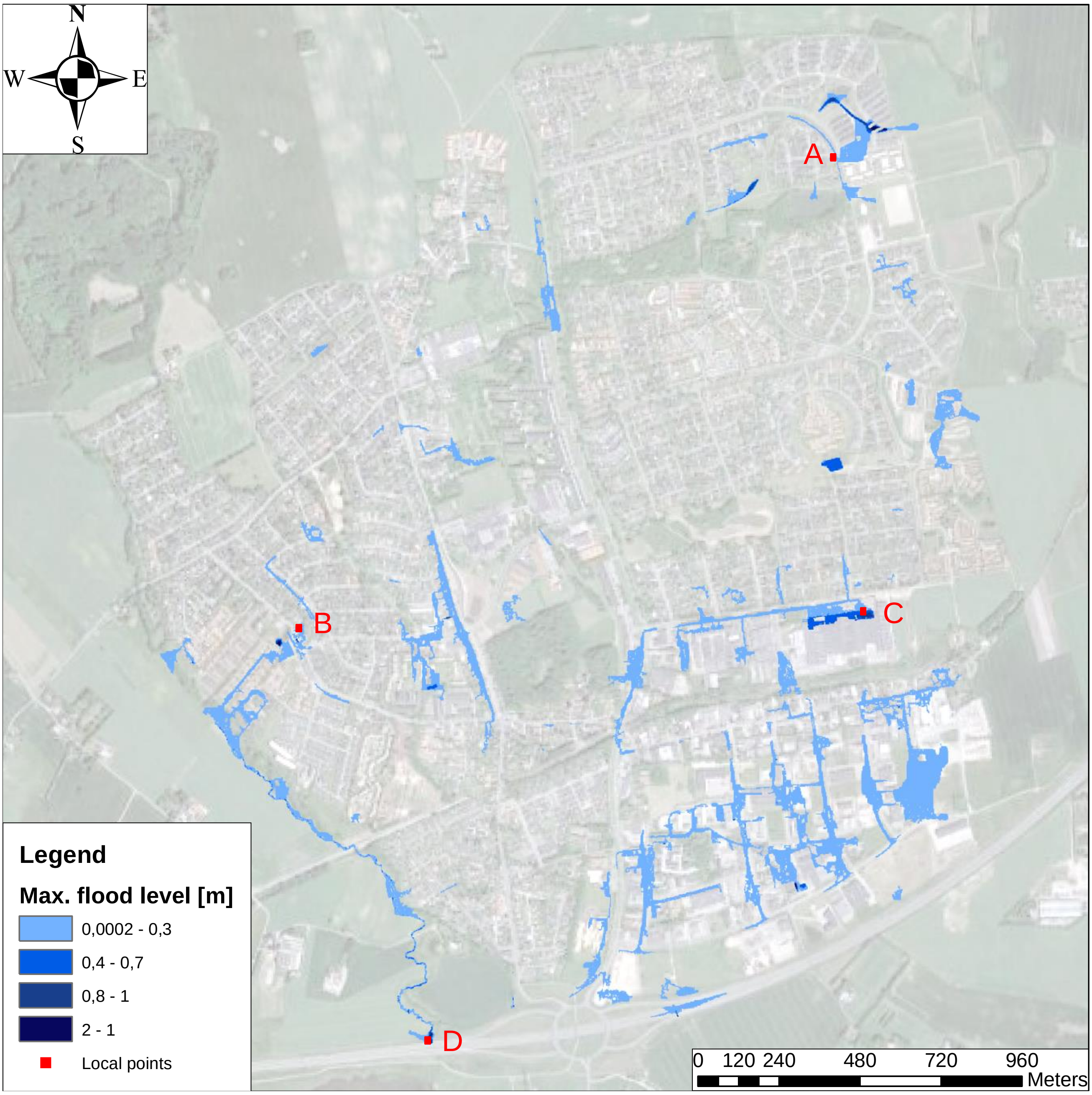


Figure 19: Maximum flood level on the 26 August 2012 showing the 4 local points.

Figure 20 shows the return period of the maximum flood level for all the 10 events obtained at point A. Results are ranked from the highest to the lowest. The highest value correspond to 8 June 1996.

a)

A		
Event	**Return period [years]**	**Max H [m]**
08/06/1996	27,00	0,23
05/05/2015	13,50	0,21
12/08/2006	9,00	0,20
01/08/2006	6,75	0,20
25/06/2007	5,40	0,20
26/08/2012	4,50	0,19
07/08/2005	3,86	0,19
24/08/1997	3,38	0,19
12/08/2002	3,00	0,18
22/08/2012	2,70	0,16

b)

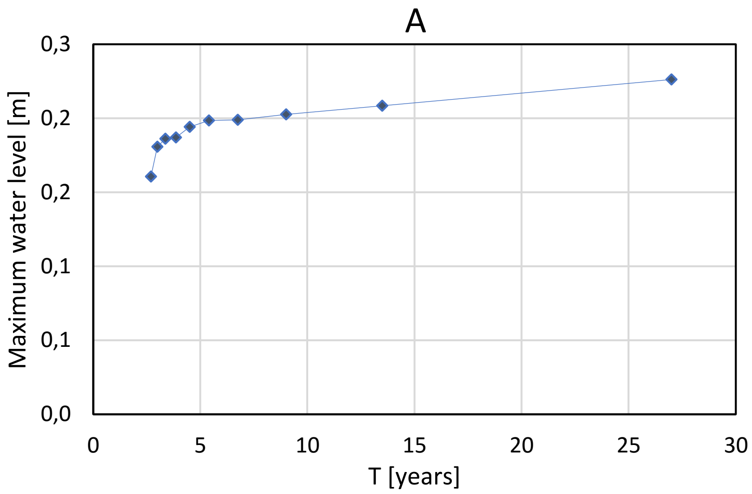


Figure 20: *a)* Table shows the maximum flood level of flood (max H) ranked at point A for the 10 events. *b)* Maximum flood level at point A versus the return period for the 10 events.

Figure 21 shows the return period of the maximum flood level for all the 10 events obtained at point B. Results are ranked from the highest to the lowest. The highest value correspond to 26 August 2012.

a)

B		
Event	**Return period [years]**	**Max H [m]**
26/08/2012	27,00	1,29
08/06/1996	13,50	1,13
01/08/2006	9,00	1,10
12/08/2006	6,75	1,07
05/05/2015	5,40	1,07
25/06/2007	4,50	1,05
07/08/2005	3,86	0,92
12/08/2002	3,38	0,83
24/08/1997	3,00	0,69
22/08/2012	2,70	0,43

b)

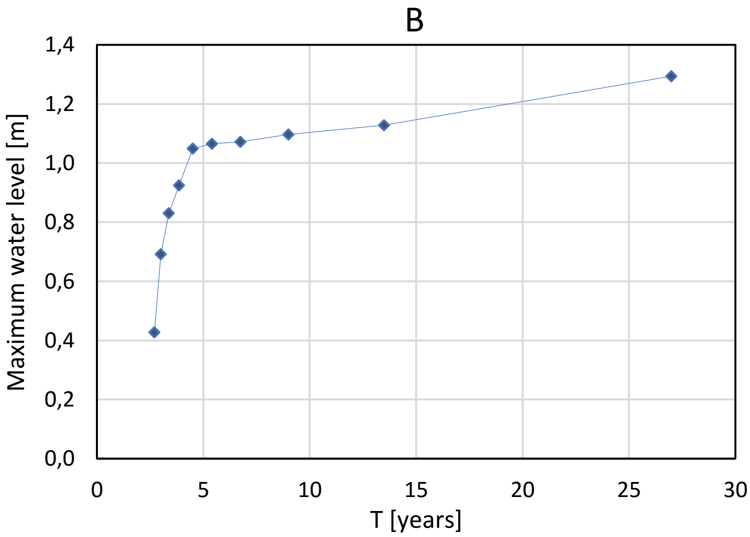


Figure 21: *a)* Table shows the maximum flood level of flood (max H) ranked at point B for the 10 events. *b)* Maximum flood level at point B versus the return period for the 10 events.

Figure 22 shows the return period of the maximum flood level for all the 10 events obtained at point C. Results are ranked from the highest to the lowest. The highest value correspond to 26 August 2012.

a)

C		
Event	**Return period [years]**	**Max H [m]**
26/08/2012	27,00	0,84
01/08/2006	13,50	0,83
25/06/2007	9,00	0,69
12/08/2002	6,75	0,68
07/08/2005	5,40	0,64
22/08/2012	4,50	0,53
12/08/2006	3,86	0,47
05/05/2015	3,38	0,43
08/06/1996	3,00	0,31
24/08/1997	2,70	0,19

b)

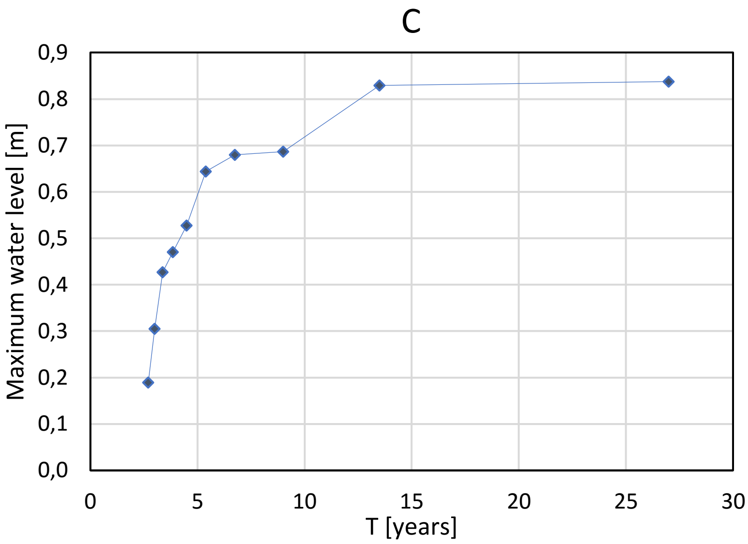


Figure 22: *a)* Table shows the maximum flood level of flood (max H) ranked at point C for the 10 events. *b)* Maximum flood level at point C versus the return period for the 10 events.

Figure 23 shows the return period of the maximum flood level for 5 events obtained at point D. These were the only events that have been flooded in that point. It is ranked from the highest to the lowest. The highest value correspond to 1 August 2006.

a)

D		
Event	**Return period [years]**	**Max H [m]**
01/08/2006	27,00	1,36
26/08/2012	13,50	1,35
12/08/2002	9,00	0,97
25/06/2007	6,75	0,97
07/08/2005	5,40	0,75
08/06/1996	4,50	0,0
12/08/2006	3,86	0,0
05/05/2015	3,38	0,0
24/08/1997	3,00	0,0
22/08/2012	2,70	0,0

b)

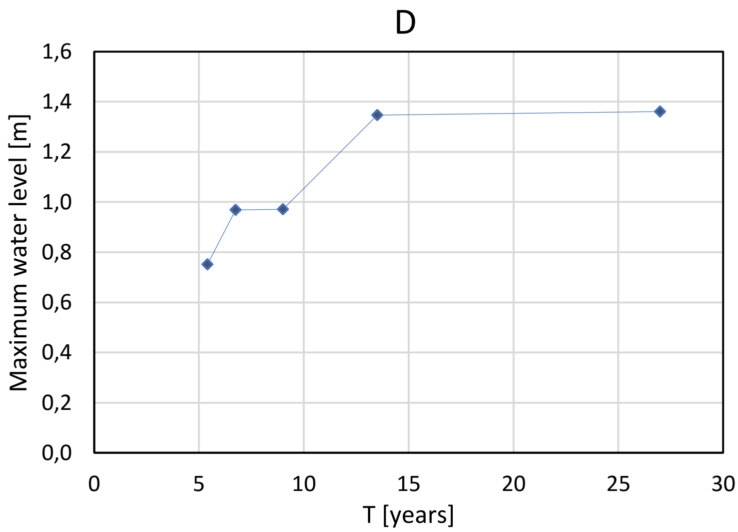


Figure 23*: a)* Table shows the maximum flood level of flood (max H) ranked in point D for the 10 events. *b)* Maximum flood level at point D versus the return period for the 10 events.

When the results of the 4 selected points are compared, the highest return period of the maximum flood level corresponds to different events for each point. For point A, the highest event correspond to 8 June 1996, for point B and point C the highest event is on 26 August 2012 and for point D is the 1 August 2006. These differences may be caused to the rainfall variability, which varies from event to event in combination to the irregular topography of the catchment.

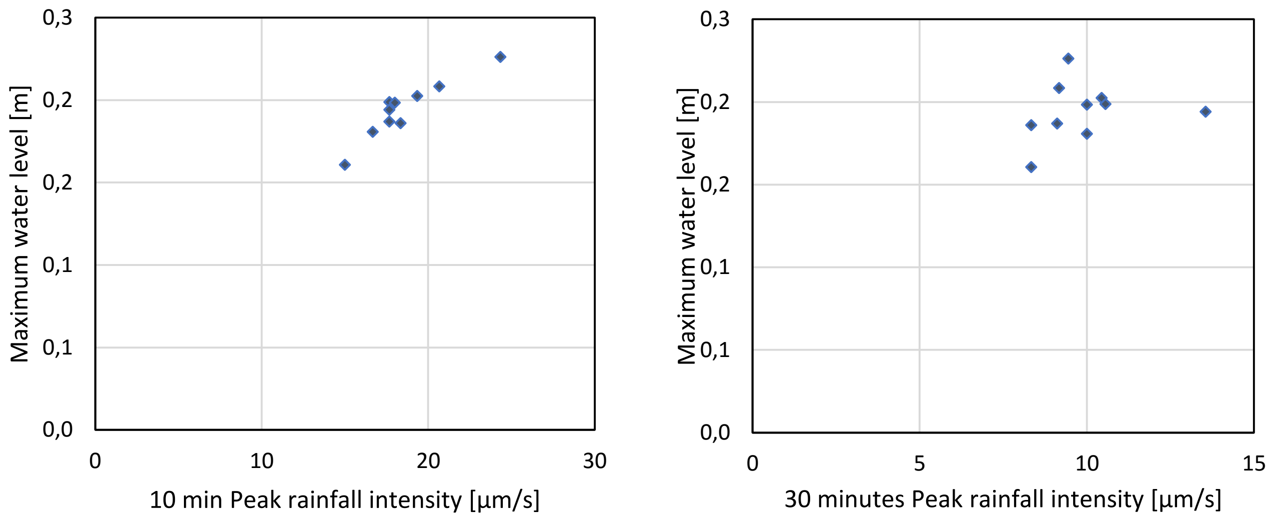
5.3.1 Estimation of aggregation time and concentration time assessment

The aim of this section is to compare the time of concentration estimated at section 5.2 with the aggregation time from the rainfall statistics. A standard aggregation time is chosen for each area, depending on the estimated time of concentration. According to the rational method (Thompson, 2006), the chosen aggregation time has to correspond with the time of concentration, as explained in section 3.3.1. For each point, two plots with different aggregation times are presented. The chosen aggregation times for peak rainfall intensity are: 10, 30, 60 and 180 minutes. Each point represents the maximum flood level for all the 10 events. The results are shown for each point individually. At the end of the section, a summary table (Table 6) shows results for all points, including the total concentration time estimated at section 5.2 and the aggregation time found in this section.

Point A

Figure 24a and b, shows how different aggregations may affect on the obtained results. As state in section 5.2, point A is close to the nearest manhole, which gives a short Ts (1 minute) and it is influenced by water coming directly from the manhole. The first plot with 10 minute aggregation time, shows a very good correlation (0,92), as the total time of concentration (12 minutes) is similar. It may be due to the fact that it is a flat area and water is coming from one manhole which is very close to the point. However, for aggregation time of 30 minutes, resulting points are more dispersed and less correlated. This might be either because water could also come from another manhole close to the point, with different concentration times in the network and the surface, or because all water has already considered. Values from Figure 24 can be viewed in Table A.8 in Appendix.

a) *b)*



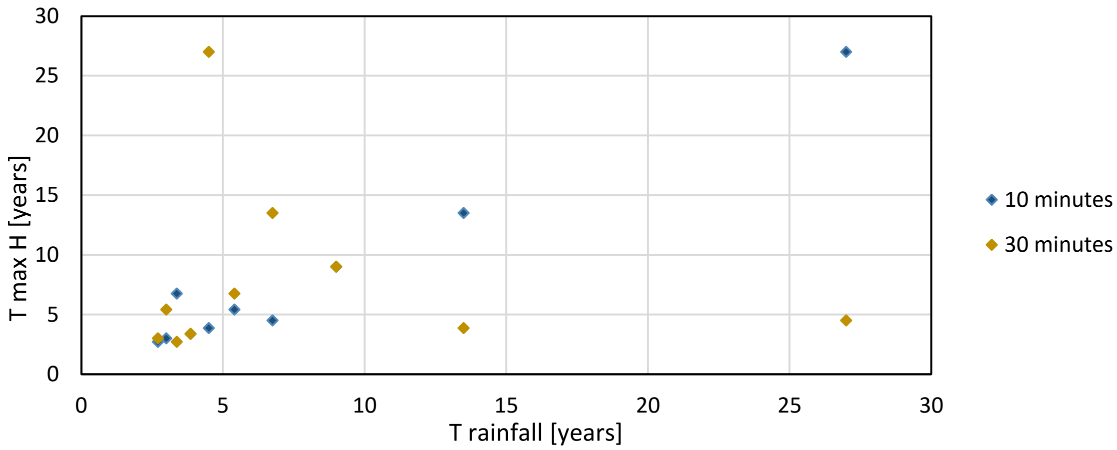
c)

	10 minutes	30 minutes
Coefficient of correlation	0,92	0,22

Figure 24: Comparison between aggregation times of 10 minutes and 30 minutes. *a)* Maximum water level versus rainfall intensity during 10 minutes at Point A for all 10 events. *b)* Maximum water level versus rainfall intensity during 30 minutes in Point A for all the 10 events. *c)* Coefficient of correlation of graphs a) for 10 minutes and b) for 30 minutes

Similar results are found when the return period of the maximum flood level and the return period of the rainfall for 10 and 30 minutes aggregation times are compared. Figure 25 shows high correlation with a 10 minutes aggregation time.

a)



b)

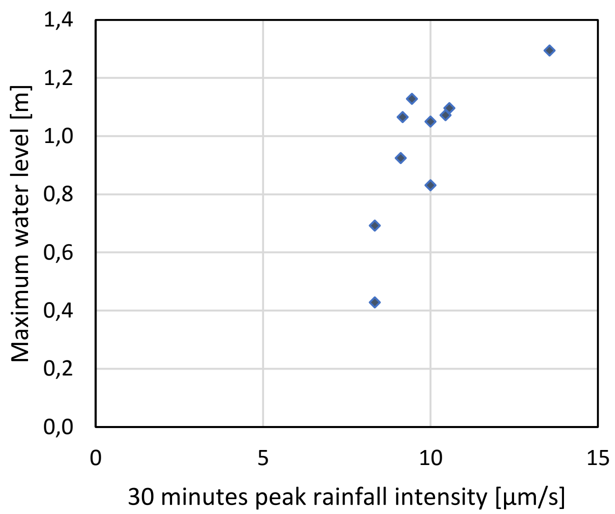
Coefficient of correlation		
	T rainfall	
	10 min	***30 min***
T max H	0,98	-0,15

Figure 25: Return period of flood depth versus return period of rainfall in point A.

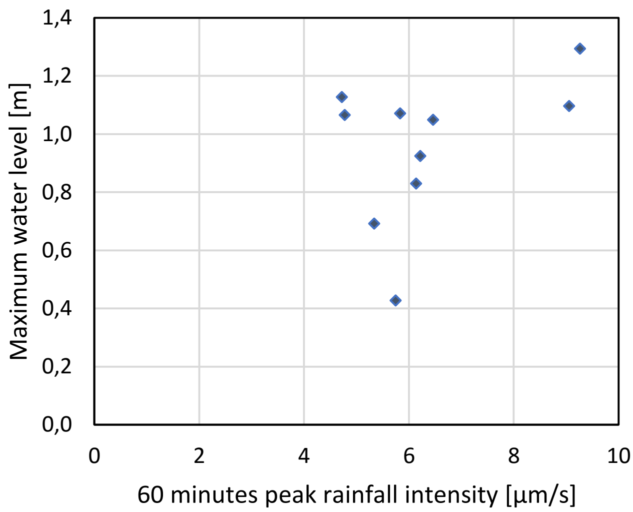
Point B

In this case, point B is more influenced by surface flood than water from the network, since the point is located in a steeper area and far for the manholes. The obtained scatter points from both aggregation times clearly indicate that water is coming from multiple manholes and is affecting to flood depth. The total concentration time was estimated to be around 38 minutes and Figure 26 confirms that for the 30 minutes aggregation time, correlation is higher. This might be due to the fact that all water already contributes to the point, so it shows better relationship than for 60 aggregation time. Values from Figure 26 can be found at Table A.9 in Appendix.

a)



b)



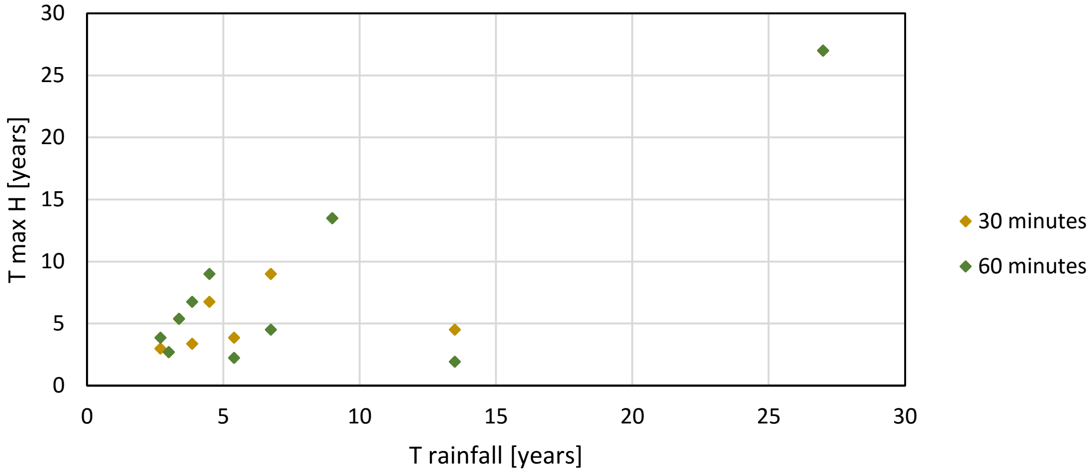
c)

	30 minutes	**60 minutes**
Coefficient of correlation	0,74	0,41

Figure 26: Comparison between aggregation times of 30 minutes and 60 minutes. *a)* Maximum water level versus rainfall intensity during 30 minutes in Point B for all 10 events. *b)* Maximum water level versus rainfall intensity during 60 minutes in Point B for all the 10 events. *c)* Coefficient of correlation of graphs a) for 30 minutes and b) for 60 minutes.

When the return period of the maximum flood level and the return period of the rainfall for 30 and 60 minutes aggregation times are compared, they show similar correlations but for 30 minutes aggregation time the results are better (Figure 27).

a)



b)

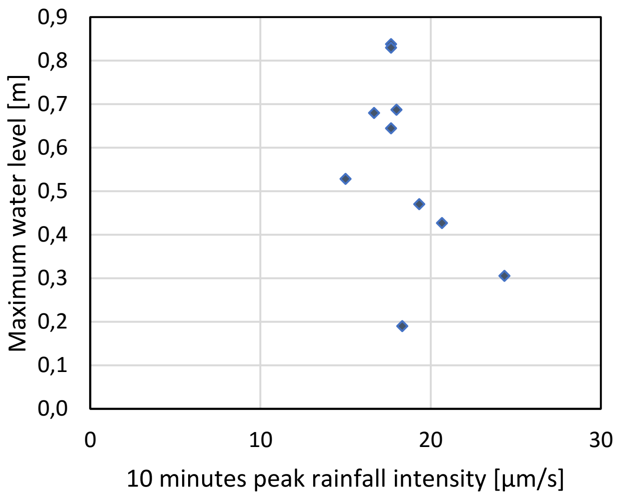
Coefficient of correlation		
	T rainfall	
	30 min	***60 min***
T max H	0,88	0,80

Figure 27: Return period of flood depth versus return period of rainfall in point B.

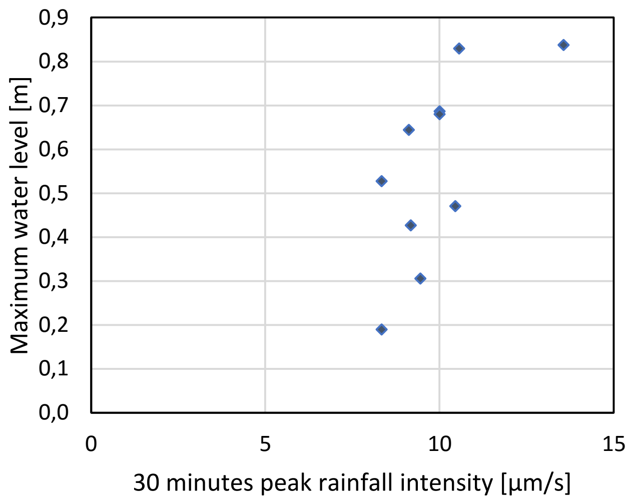
Point C

Figure 28 shows a very dispersive scatter points for Point C, this may be caused by the influence of surface flood, as it is far from the surcharged manholes and the contributing area has a significant slope. In addition, water can come from different manholes affecting the flood depth. The time of concentration of the surface runoff has been estimated to be around 11 minutes, and the total concentration time (including the network system concentration time) is around 23 minutes. When 10 minutes and 30 minutes aggregation times are plotted, a negative correlation are found for 10 minutes. However, a better correlation is found for the 30 minutes which is very similar to the total concentration time. In 30 minutes, most of the water contributes to the point. Values from Figure 28 can be found at Table A.10 in Appendix.

a)



b)



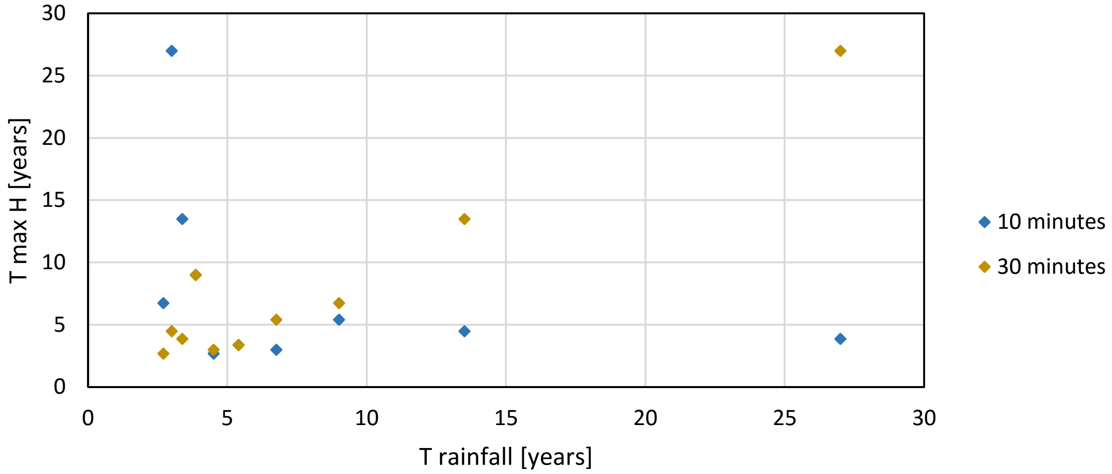
c)

	10 minutes	30 minutes
Coeficient of correlation	-0,52	0,54

Figure 28: Comparison between aggregation times of 10 minutes and 30 minutes. *a*) Maximum water level versus rainfall intensity during 10 minutes in Point C for all 10 events. *b)* Maximum water level versus rainfall intensity during 30 minutes in Point C for all the 10 events. *c)* Coefficient of correlation of graphs a) for 10 minutes and b) for 30 minutes.

Similar results are found when the return period of the maximum flood level and the return period of the rainfall for 10 and 30 minutes aggregation times are compared. Figure 29 shows a high correlation for a 30 minutes aggregation time.

a)



b)

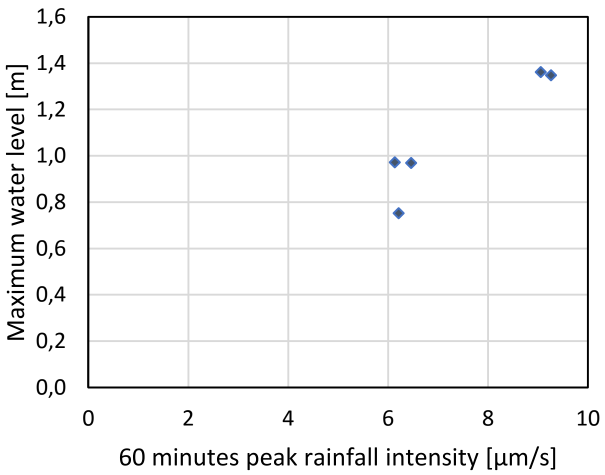
Coefficient of correlation		
	T rainfall	
	10 min	**30 min**
T max H	-0,36	0,96

Figure 29: Return period of flood depth versus return period of rainfall in point C.

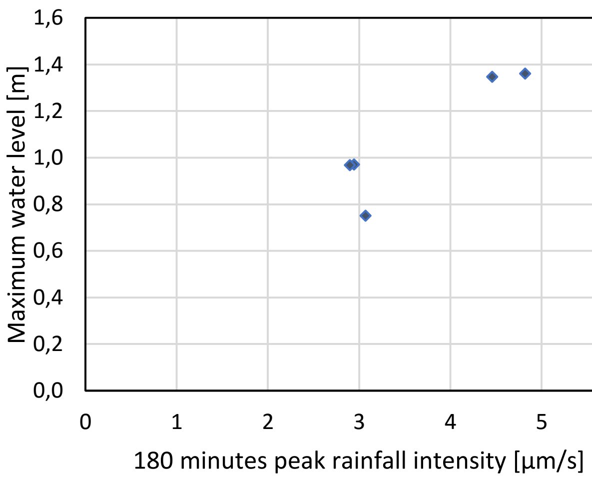
Point D

As described in section 5.2, point D is highly influenced by surface flooding because the surcharged manholes are located far from the selected point and the area is steep. A time of concentration of more than 2 hours is estimated for point D. When a rainfall intensity for aggregation time of 60 minutes is plotted, results at Figure 30 show similar correlations than for aggregation time of 180 minutes. This could be caused by the fact that water already contributes to the point for both aggregation times. Selecting the 180 minutes ensures that all the water is contributing to the point. In addition, the high correlation for both aggregation times is probably due to just a few points are included. Values from Figure 30 can be found in Table A.11 in the Appendix.

a)



b)



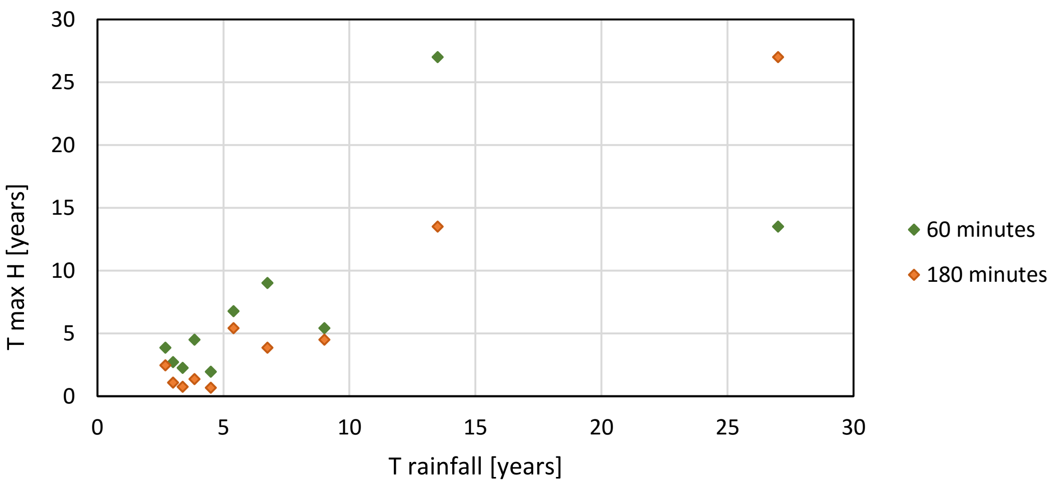
c)

	60 minutes	180 minutes
Coeficient of correlation	0,94	0,91

Figure 30: Comparison between 60 minutes and 180 minutes of the aggregation time. a) Maximum water level versus rainfall intensity during 60 minutes in Point D for all 10 events. b) Maximum water level versus rainfall intensity during 180 minutes in Point D for all the 10 events. c) Coefficient of correlation of graphs a) for 60 minutes and b) for 180 minutes.

When the return period of maximum flood level and the return period of rainfall are compared, a slight difference from the results obtained before is found (Figure 31). By considering an aggregation time of 180 minutes, results present very high correlation.

a)



b)

Coefficient of correlation		
	T rainfall	
	60 min	***180 min***
T max H	0,62	0,98

Figure 31: Return period of flood depth versus return period of rainfall in point C.

Table 6 shows a summary of the results from the total time of concentration found at section 5.2 and the chosen aggregation times for each point.

Table 6: Total time of concentration for each point and aggregation times chosen.

Points [-]	Total Tc [min]	Aggregation time [min]
A	12	10
B	38	30
C	23	30
D	141	180

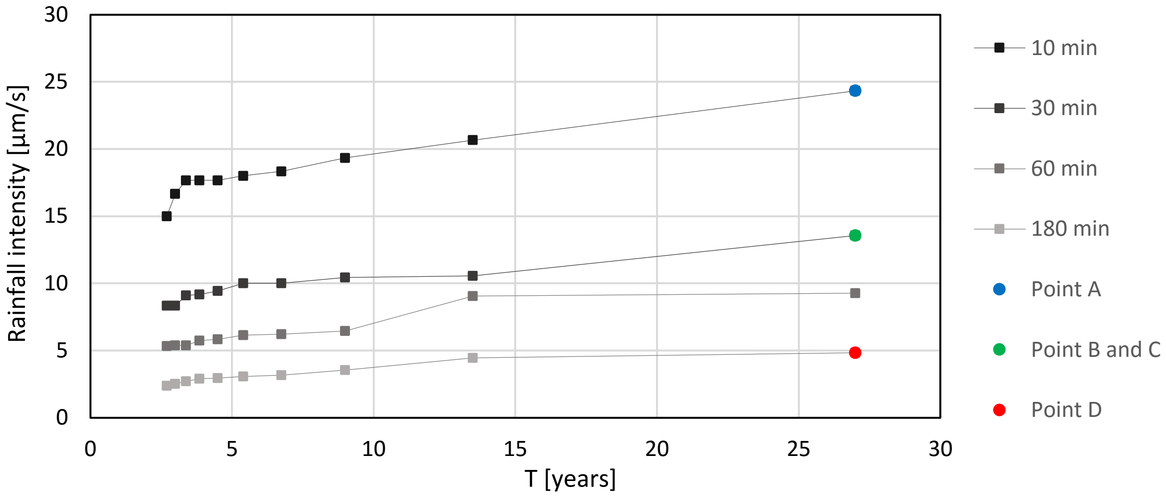
5.3.2 Comparison with rainfall statistics

Once the aggregation time has been defined for each local point, the return period of maximum flood level is compared with the return period of the rainfall.

Figure 32 shows the return period of the rainfall for the 10 events versus the peak rainfall intensity for aggregation times of 10, 30, 60 and 180 minutes. The coloured scatter points indicate the highest return period of the maximum flood level at the 4 local points for the 10 events.

By plotting the critical aggregation times at each point, the events with the highest return period of maximum flood level do not always coincide. The table found in Figure 32b shows only the highest event at each point, and it can be seen that for the highest return period (27 years), the events are different at each point. The only event that is repeated is the 26 August 2012 which is the highest return period of the flood level for both points B and C. These differences could be due to the catchment irregularities and another fact is that by applying historical rain series, the rainfall is varying from event to event.

a)



b)

Events	Points	T rainfall [years]	Duration [min]	Rainfall intensity [µm/s]
08/06/1996	A	27	10	24,33
26/08/2012	B	27	30	13,56
26/08/2012	C	27	30	13,56
01/08/2006	D	27	180	4,82

Figure 32: The peak rainfall intensity for the minutes: 10, 30, 60 and 180 versus the return period of rainfall is plotted and compared in the 4 points.

Discussion

Some of the outcomes found in that section are:

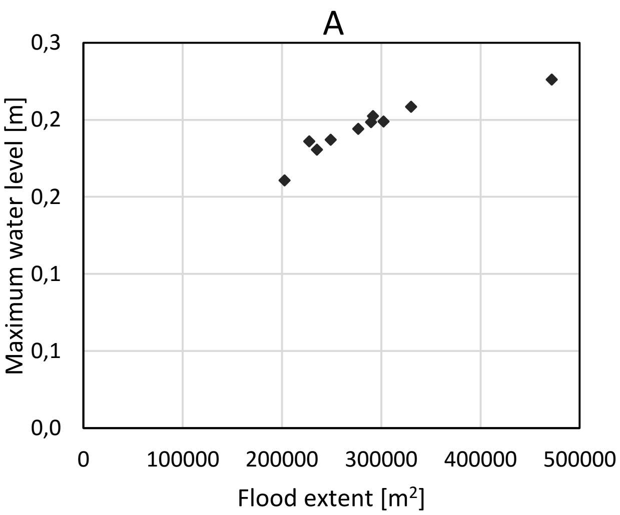
- The maximum flood level of the surface flood is different for each of the 4 local points.
- The events with the higher return period are not the same for each point.
- The return period of rainfall and the return period of the flood based on the maximum flood level is not the same for each event and each point.

5.4 Flood extent and volume comparison with maximum flood level

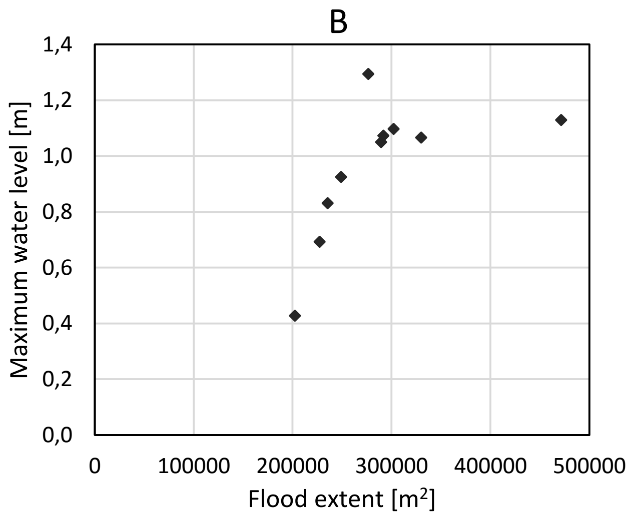
In this section, the maximum flood extent and the maximum flood volume for the whole catchment are compared with the maximum flood level for the selected local points.

Figure 33 shows 4 plots representing the flood extent versus the maximum flood level at each point for the 10 events. The correlation for each of the plots is shown below. For point A, the scatter points shown at Figure 33a have a very good correlation since the point is very close to the surcharged manhole and it is located in a flat area, so water is not flowing or accumulating in urban areas. As the flood extent increases at each event, a higher amount of water is in the catchment and the water level is higher. However, for points B, C and D the slope is higher and water flows through the surface from other surcharged manholes and accumulating at specific areas. For these points, the correlation of the flood extent and water level is weak and even negative.

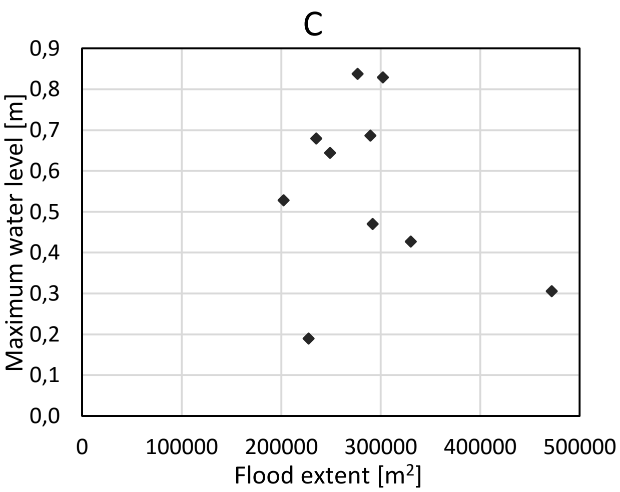
a)



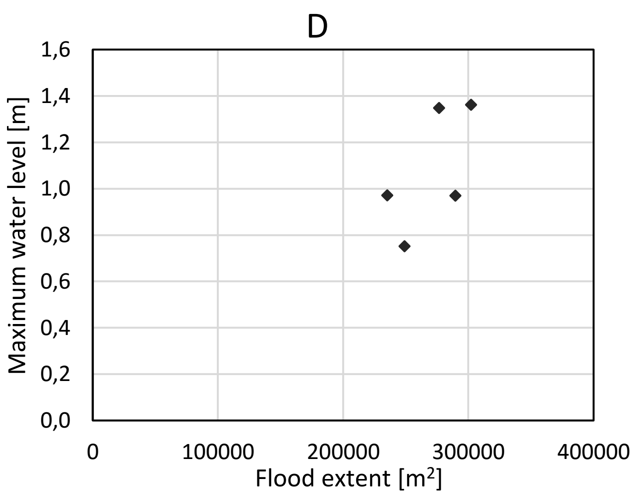
b)



c)



d)



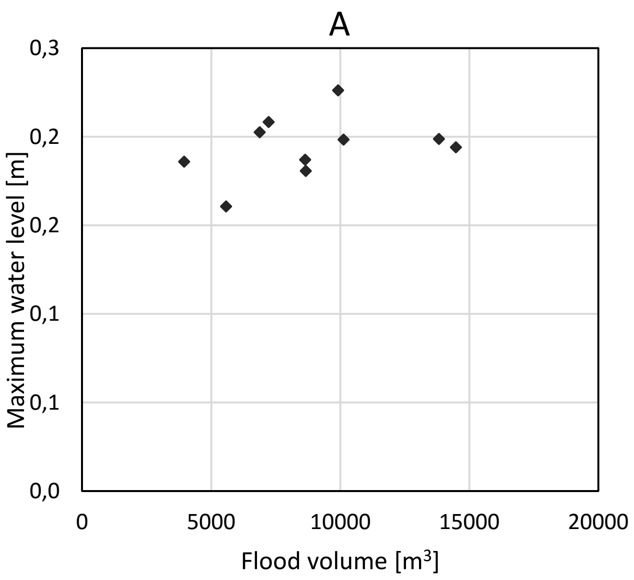
e)

Points	Coefficient of correlation
A	0,92
B	0,61
C	-0,25
D	-0,18

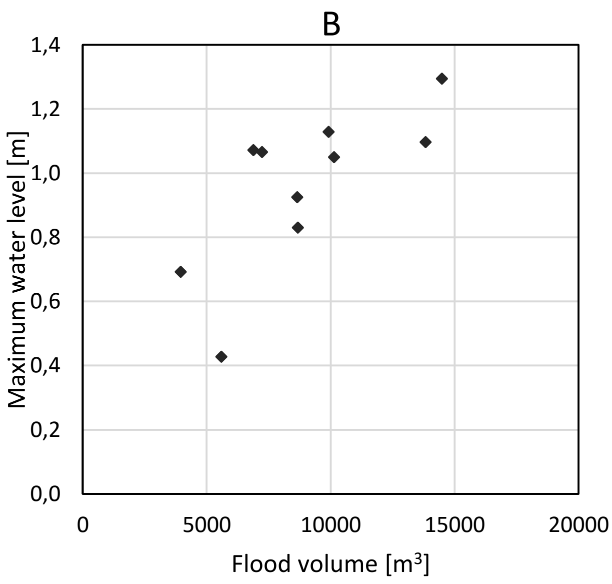
Figure 33: Comparison between Maximum flood level, in each of the study points, and Total flood extent, for the whole catchment. e) Coefficient of correlation for Maximum flood level and Total flood extent in each point.

Figure 34 shows the relation between the maximum flood volume for whole catchment and the maximum water level at the selected points for each event. It is clearly that for point A a weak correlation is found. This is caused by the fact that there is less surface accumulation since it is located in a flat area and it is more dependent to water coming out from the network system. On the other hand, points B, C and D are more influenced by surface flood and their correlations are high. Water is accumulating in pounds, so as higher the flood level is, higher is the volume.

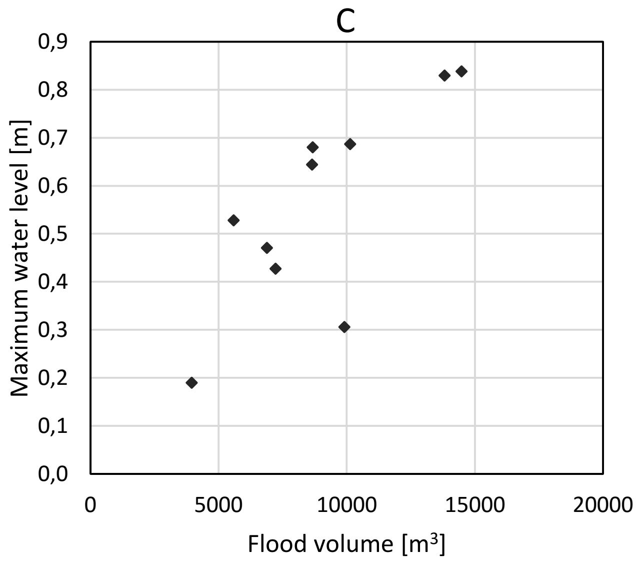
a)

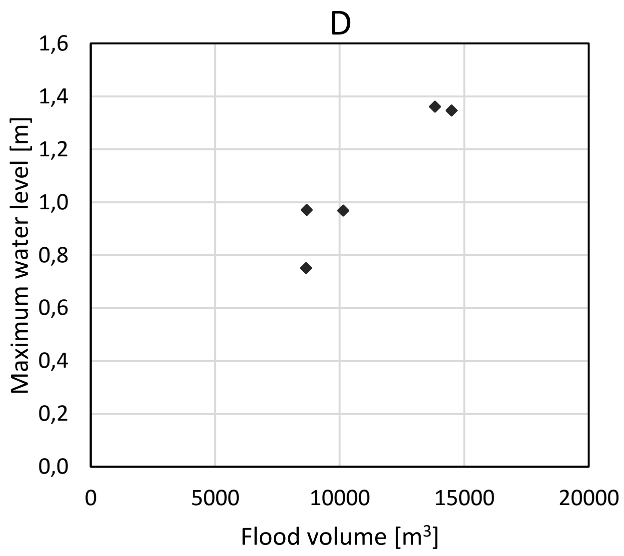


b)



c) *d)*





e)

Points	Coefficient of correlation
A	0,34
B	0,74
C	0,78
D	0,83

Figure 34: Comparison between Maximum flood level, in each of the study points, and Total flood volume, for the whole catchment. e) Coefficient of correlation for Maximum flood level and Total flood volume in each point.

Discussion

- By comparing the maximum flood level and the maximum flood extent, it is found that differences between points have in some cases good correlation and in some others negative correlation. Another fact mainly caused the variability of the catchment and rainfall.
- By comparing the maximum flood level and the maximum flood volume, a better correlation is found comparing to the flood extent instead.
- The higher is the maximum water level, the higher is the maximum flood volume in all the catchment.

6. Conclusions and future work recommendations

In the project an analysis was made to assess the return period of flood considering a specific catchment and applying historical rain series. The catchment of study has the peculiarity of having large terrain variability with steep and flat areas, as well as having a complex urban drainage system and dynamics of flow paths on surface.

Flood modelling was used in order to obtain the maximum flood level, maximum flood volume and maximum flood extent from the selected catchment. These variables were analysed to see the differences found by considering an irregular catchment and variable rainfall. Flood events are quite rare, therefore little knowledge on the nature of floods and interaction between the surface and drainage. So, only 10 events are consider for the analysis in this project to derive as much as possible from these events. In addition, it is assumed that the model is correct and can represent the hydraulic behaviour of floods. The model was calibrated using the rain events on 26 August 2012 and 13-14 July 2014 which means that some of the floods results might be overestimated. However, this project investigates only relative comparisons.

It was found that the correlation between the flood volume and flood extent from the whole catchment is weak, which might indicate large variability in flood depths locally. In addition, the event with the highest return period of flood volume was not the same as the event with the highest return period of flood extent, thereby confirming the irregularity on the catchment. Therefore it is important to emphasise whether a return period of a flood is estimated by volume, extent or depth.

Since it was found a weak correlation between the flood volume and the flood extent in the whole catchment, an analysis of 4 local flooding areas was proceed. It was found different maximum flood level values in the 4 different local points in the catchment. This could be due to the surface flooding behaving differently throughout the catchment. It depends on the topography and the network system of the area where the points are located. When the area is mostly flat, the water flood level is more influenced by water surcharging directly from the network system, but if the area is steep, water is transported on the surface and accumulating in urban areas, causing flooding. On the other hand, if the contributing area is big, more rain water is in the system and could affect the water flood level. Additionally, the maximum flood level could also be contributed from multiple manholes and it depends on how far are the local points from these manholes. Consequently, the highest return period of maximum flood level is not the same in each point.

When the maximum flood level is compared with the maximum flood volume a better correlation was seen that comparing the maximum flood level with the maximum flood extend. With aggregations times of 30 and 60 minutes a good correlation was found between the return period of flood volume and the rainfall, but a poor correlation is found when the return period of flood extent and the rainfall are compared instead. It should be noted that the flood extent can vary considerably with different flood levels. So it means that for a small flood depth the flood extent can be very large.

For each of the local points, the time of concentration of the catchment was estimated in this study considering synthetic rain series. It was done in order to choose an appropriate aggregation time of the rainfall for each point. The results show different times of concentration in the whole catchment, this can be possible due to the catchment is irregular. The time of concentration is longer in large contribution areas, in more flat surfaces and with long distances between the surcharged manholes and local points. Different times of aggregation were analysed and compared with the time of concentration found. The flatter areas have more influence from water coming directly to network system and have low aggregation times, showing better and linear relationship. In more steep areas there is a more influence from water coming from multiple manholes showing a large variability and more complexity in flow pattern.

As the catchment has different times of concentration, the events, which the return period of flood level and the return period of rainfall is the highest, were not the same. It could be due to the fact that rainfall varies from event to event and it also may be because the catchment has an irregular topography.

On the basis of the results, a first approach to assess the return period of flood for an irregular catchment and by applying historical rain series can be done. It has seen a weak correlation when the flood extent is analysed and compared with rainfall statistics. The maximum flood level has been analysed in different local points which have also been observed differences between them. However, it is seen that by analysing the maximum flood volume the results shows a better correlation between the variables and comparing it with the statistics of rainfall.

The relationship between the return period of the rain and the return period of the flood level is not unambiguous due to the complexity of the urban drainage systems, the dynamics of the surface flow and ponding as well as the dynamics of the rainfall. Therefore is important to emphasise the use of historical rain series in flood analysis rather than design storms or statistical rainfall.

In order to simulate the complex dynamics of a flood in a catchment with large terrain variability (steep catchment for danish conditions) it is recommended to use detailed flood models with dynamical rainfall inputs in order to estimate the return period of a given flood.

Recommendations for future work

The research in that study has focused on assessing the return period of flood for an irregular catchment by applying historic rain series. However, it would be interesting to investigate further and some instances are proposed in this section.

The same study could be done by applying different historical rain events in order to see the behaviour of surface flood in the same catchment. As an alternative, it could be relevant to look at the spatial variability of rain with more than one rain gauge as input. In addition, it could be an idea to choose another catchment with different topographic characteristics with the historical rain series applied in this study and compare the differences between both studies.

The catchment selected in this study is a separate drainage system, so another proposal could be to do the same type of analysis but with a combined drainage system which collects the sewage and storm water at the same time, so more inflow is considering in the analysis.

There are also several minor changes which may improve or change the results. For instance, it would improve the results by simulating the flow of the streams. Other changes may be choosing another methods to select the most extreme events from the historical rain series.

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A. Additional tables

Table A.1 show the total 21 events generated by the job list and the total number of surcharged manholes for these 21 events.

Table A.1: Total number of surcharged manholes for the 21 events.

Events	Nº of nodes surcharged
05/07/1991	21
29/06/1994	31
17/08/1994	20
18/08/1994	63
08/06/1996	408
24/08/1997	173
19/08/1999	36
17/08/2000	48
12/09/2000	29
28/07/2001	102
12/08/2002	156
07/08/2005	172
01/08/2006	193
12/08/2006	220
25/06/2007	201
19/09/2007	86
12/07/2010	73
22/08/2012	118
26/08/2012	178
27/07/2013	143
05/05/2015	250

Tables A.2 contain the values from the flood extent and flood volume results for the 10 events

Table A.2: Flood extent and flood volume for the 10 events

Events	Flood extent [m^2]	Flood volume [m^3]
08/06/1996	471772	9914
05/05/2015	330132	7224
01/08/2006	302208	13821
12/08/2006	291720	6883
25/06/2007	289668	10135
26/08/2012	276788	14485
07/08/2005	249052	8645
12/08/2002	235356	8671

24/08/1997	227400	3949
27/07/2013	211460	4025
22/08/2012	202500	5582

The following tables show the ranked return period of maximum flood volume and maximum flood extend for the 10 events as well as the return period of rainfall for 10, 30 and 60 minutes aggregation time.

Table A.3: Return period of volume and return period of rainfall for 10, 30 and 60 minutes aggregation time

Events	**Return period of flood volume**	**Return period of rainfall**		
		10 min	**30 min**	**60 min**
26/08/2012	27	3,86	27	27
01/08/2006	13,5	4,5	13,5	13,5
25/06/2007	9	5,4	6,75	9
08/06/1996	6,75	27	4,5	1,93
12/08/2002	5,4	3,00	5,4	5,4
07/08/2005	4,5	3,38	3,38	6,75
05/05/2015	3,86	13,5	3,86	2,25
12/08/2006	3,38	9	9	4,5
22/08/2012	3	2,7	3,00	3,86
24/08/1997	2,46	6,75	2,7	2,7

Table A.4: Return period of extent and return period of rainfall for 10, 30 and 60 minutes aggregation time

Events	**Return period of flood extend**	**Return period of rainfall**		
		10 min	**30 min**	**60 min**
08/06/1996	27	27	4,5	1,93
05/05/2015	13,50	13,5	3,86	2,25
01/08/2006	9	4,5	13,5	13,5
12/08/2006	6,75	9	9	4,5
25/06/2007	5,40	5,4	6,75	9
26/08/2012	4,50	3,86	27	27
07/08/2005	3,86	3,38	3,38	6,75
12/08/2002	3,38	3,00	5,4	5,4
24/08/1997	3	6,75	2,7	2,7
22/08/2012	2,45	2,7	3,00	3,86

Next tables show the flood extend and flood volume ranked and the rain depth for the 10 selected events

Table A.5: Flood extend and rain depth for the 10 events

Events	Flood extend [m^2]	Depth [mm]
08/06/1996	471772	17
05/05/2015	330132	17,2
01/08/2006	302208	56,2
12/08/2006	291720	21
25/06/2007	289668	37,6
26/08/2012	276788	51,6
07/08/2005	249052	33,2
12/08/2002	235356	34,8
24/08/1997	227400	19,2
22/08/2012	202500	25,2

Table A.6: Flood volume and rain depth for the 10 events

Events	Flood Volume [m^3]	Depth [mm]
26/08/2012	1448	51,6
01/08/2006	13821	56,2
25/06/2007	10134	37,6
08/06/1996	9914	17
12/08/2002	8670	34,8
07/08/2005	8644	33,2
05/05/2015	7223	17,2
12/08/2006	6883	21
22/08/2012	5582	25,2
24/08/1997	3949	19,2

In the next table the coordinates of the local points is given.

Table A.7: Additional information about the local points.

	Coordinates [UTM]	
	x	**y**
Point A	577347,27	6234243,48
Point B	575753,4	6232818,96
Point C	577433,41	6232889,22
Point D	576146,36	6231623,8

Maximum flood level and time of aggregation for the 4 local points in all the 10 selected events

Table A.8: Flood depth and rainfall intensities for aggregation times of 10 minutes and 30 minutes for the 10 events in point A.

Point A			
Events	**max H [m]**	**Rainfall intensity [µm/s]**	**Rainfall intensity [µm/s]**
		10 min	**30 min**
08/06/1996	0,23	24,33	9,44
05/05/2015	0,21	20,67	9,17
12/08/2006	0,20	19,33	10,44
01/08/2006	0,20	17,67	10,56
25/06/2007	0,20	18,00	10
26/08/2012	0,19	17,67	13,56
07/08/2005	0,19	17,67	9,11
24/08/1997	0,19	18,33	8,33
12/08/2002	0,18	16,67	10
22/08/2012	0,16	15,00	8,33

Table A.9: Flood depth and rainfall intensities for aggregation times of 10 minutes and 30 minutes for the 10 events in point B.

Point B			
Events	**max H [m]**	**Rainfall intensity [µm/s]**	**Rainfall intensity [µm/s]**
		30 min	**60 min**
26/08/2012	1,29	13,56	9,26
08/06/1996	1,13	9,44	4,72
01/08/2006	1,10	10,56	9,06
12/08/2006	1,07	10,44	5,83
05/05/2015	1,07	9,17	4,78
25/06/2007	1,05	10	6,46
07/08/2005	0,92	9,111	6,22
12/08/2002	0,83	10	6,13
24/08/1997	0,69	8,33	5,33
22/08/2012	0,43	8,33	5,74

Table A.10: Flood depth and rainfall intensities for aggregation times of 10 minutes and 30 minutes for the 10 events in point c

Point C			
Events	max H [m]	Rainfall intensity [µm/s]	Rainfall intensity [µm/s]
		10 min	30 min
26/08/2012	0,838	17,66	13,55
01/08/2006	0,829	17,66	10,55
25/06/2007	0,686	17,99	10
12/08/2002	0,680	16,66	10
07/08/2005	0,644	17,66	9,11
22/08/2012	0,528	14,99	8,33
12/08/2006	0,470	19,33	10,44
05/05/2015	0,427	20,66	9,16
08/06/1996	0,305	24,33	9,44
24/08/1997	0,189	18,33	8,33

Table A.11: Flood depth and rainfall intensities for aggregation times of 10 minutes and 30 minutes for the 10 events in point D

Point D			
Events	max H [m]	Rainfall intensity [µm/s]	Rainfall intensity [µm/s]
		60 min	180 min
01/08/2006	1,36	9,055	4,82
26/08/2012	1,34	9,262	4,46
12/08/2002	0,97	6,133	2,945
25/06/2007	0,96	6,462	2,901
07/08/2005	0,75	6,216	3,07
08/06/1996	0	4,722	1,574
12/08/2006	0	5,833	1,944
05/05/2015	0	4,777	1,592
24/08/1997	0	5,333	1,778
22/08/2012	0	5,744	2,333

B. Flood depth for the 10 events

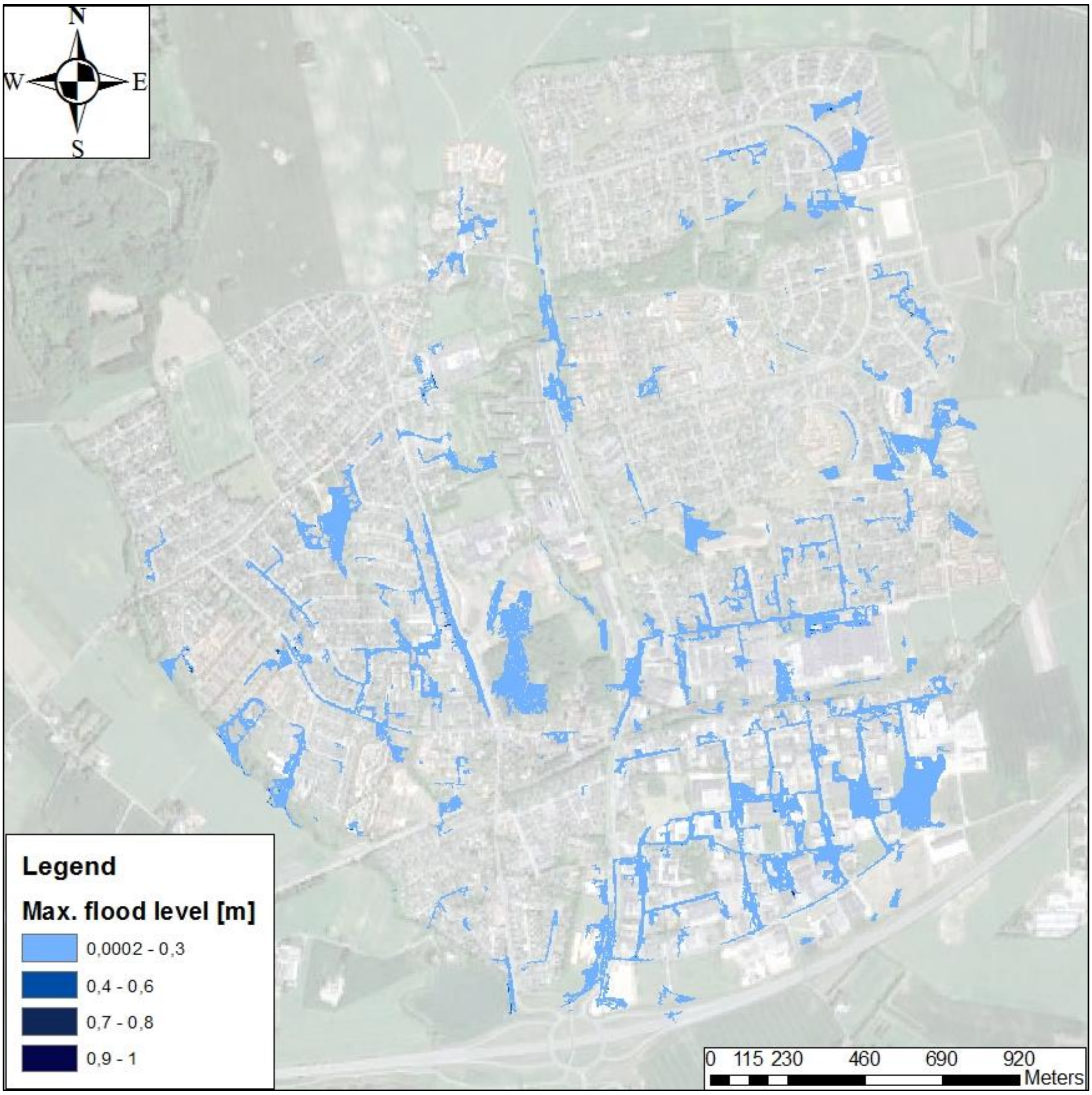

Figure B1: Maximum flood level on 6 June 1996

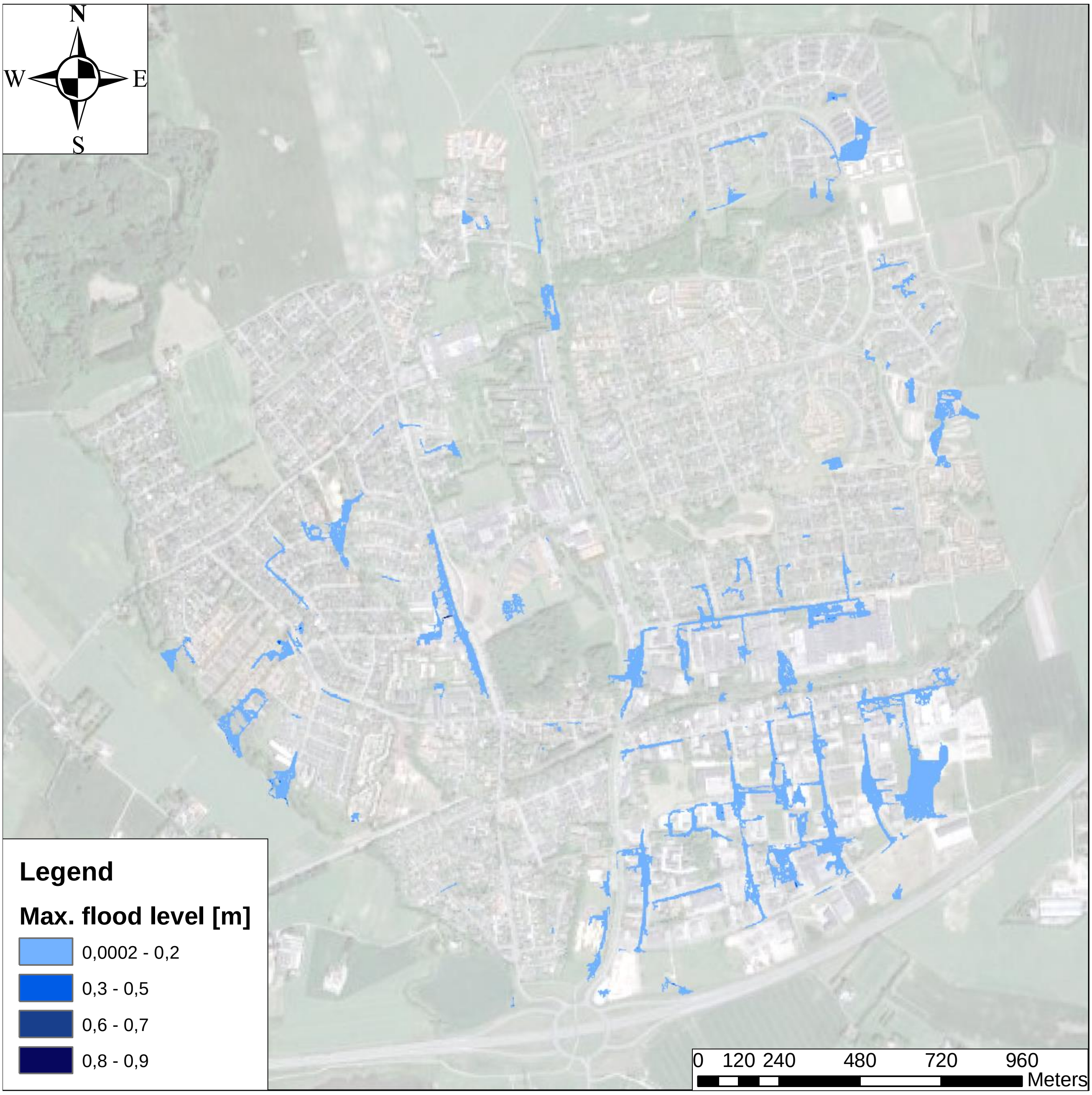

Figure B2: Maximum flood level on 24 August 1997

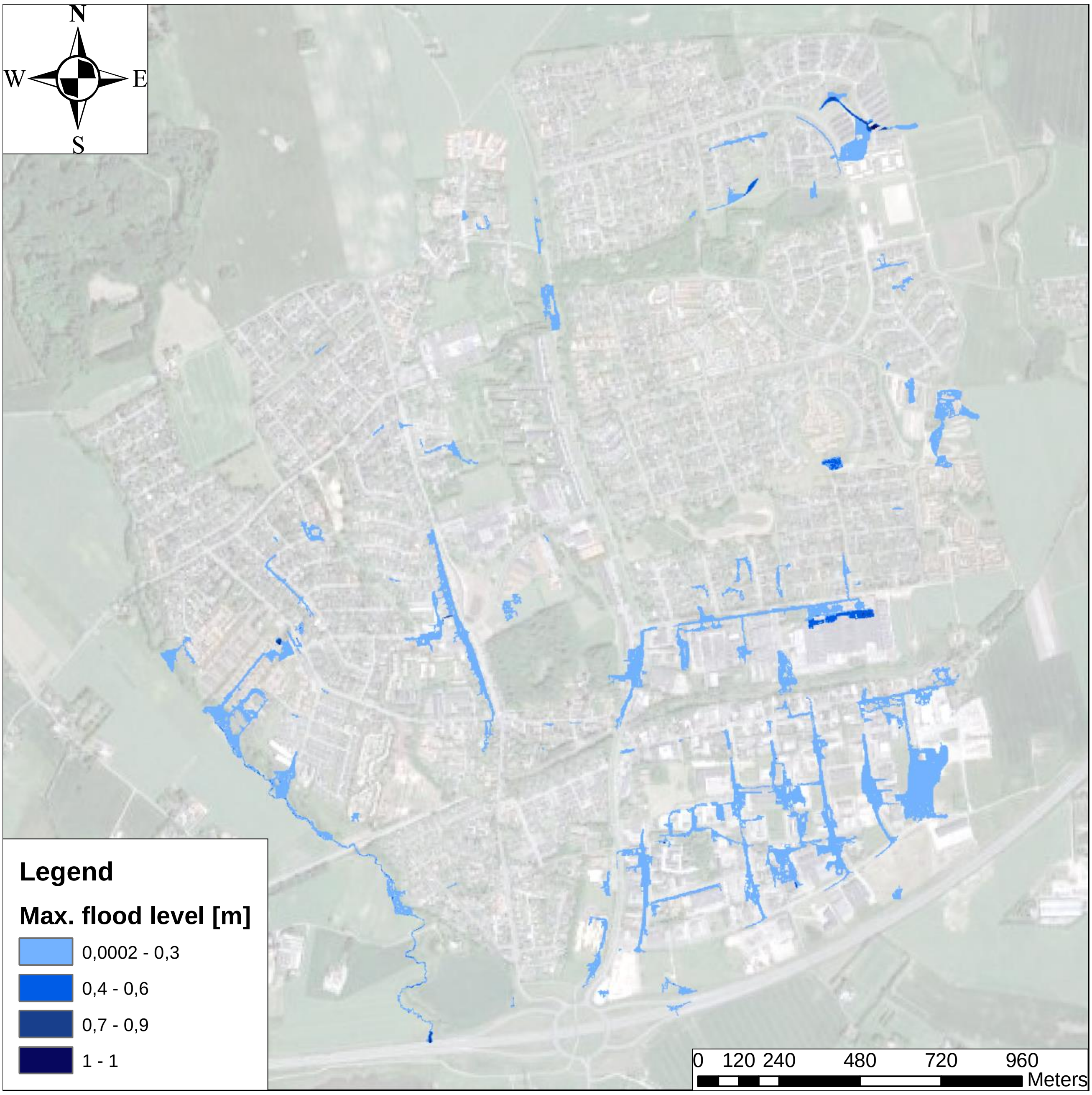

Figure B3: Maximum flood level on 12 August 2002

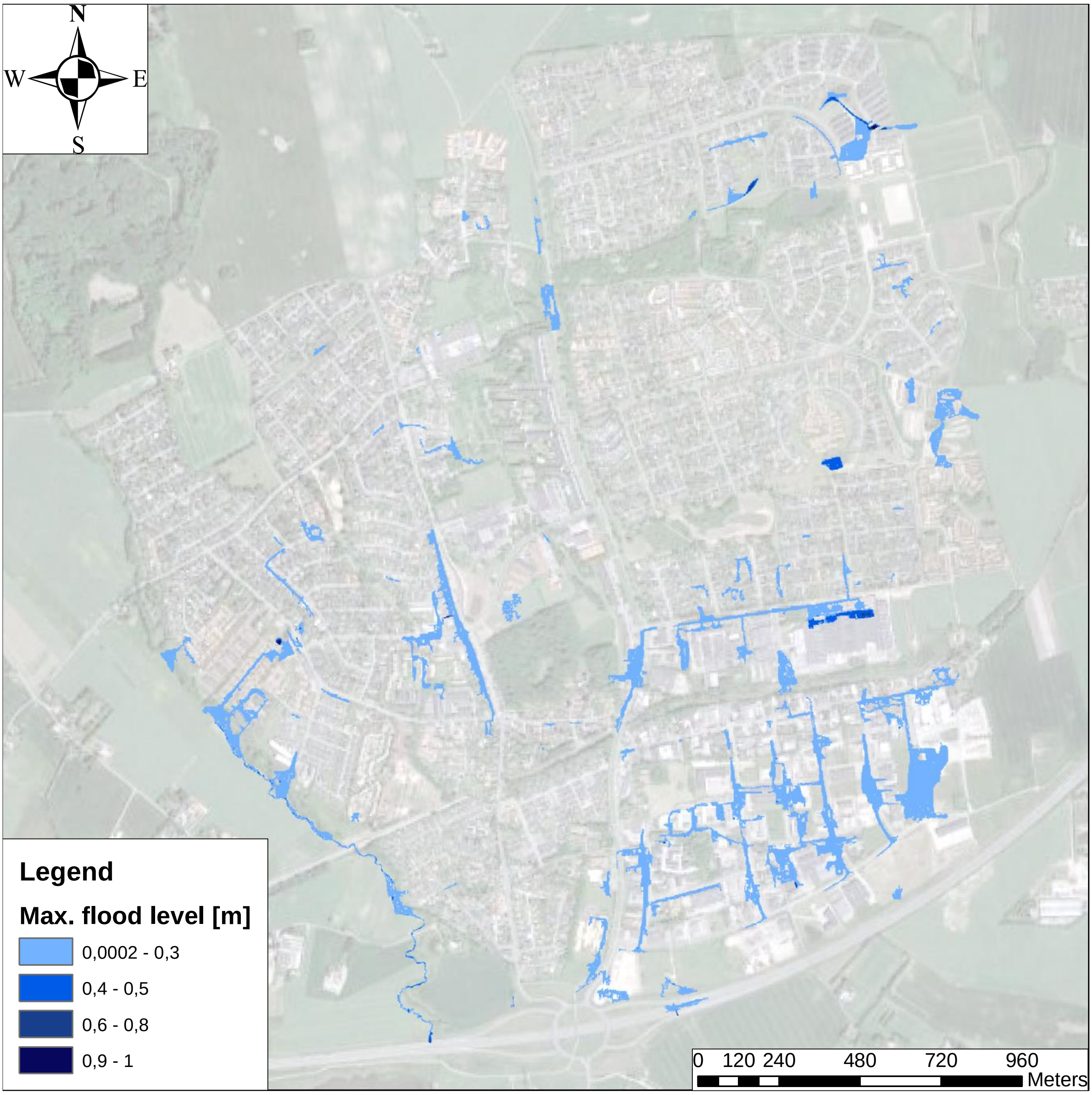

Figure B4: Maximum flood level on 7 August 2005

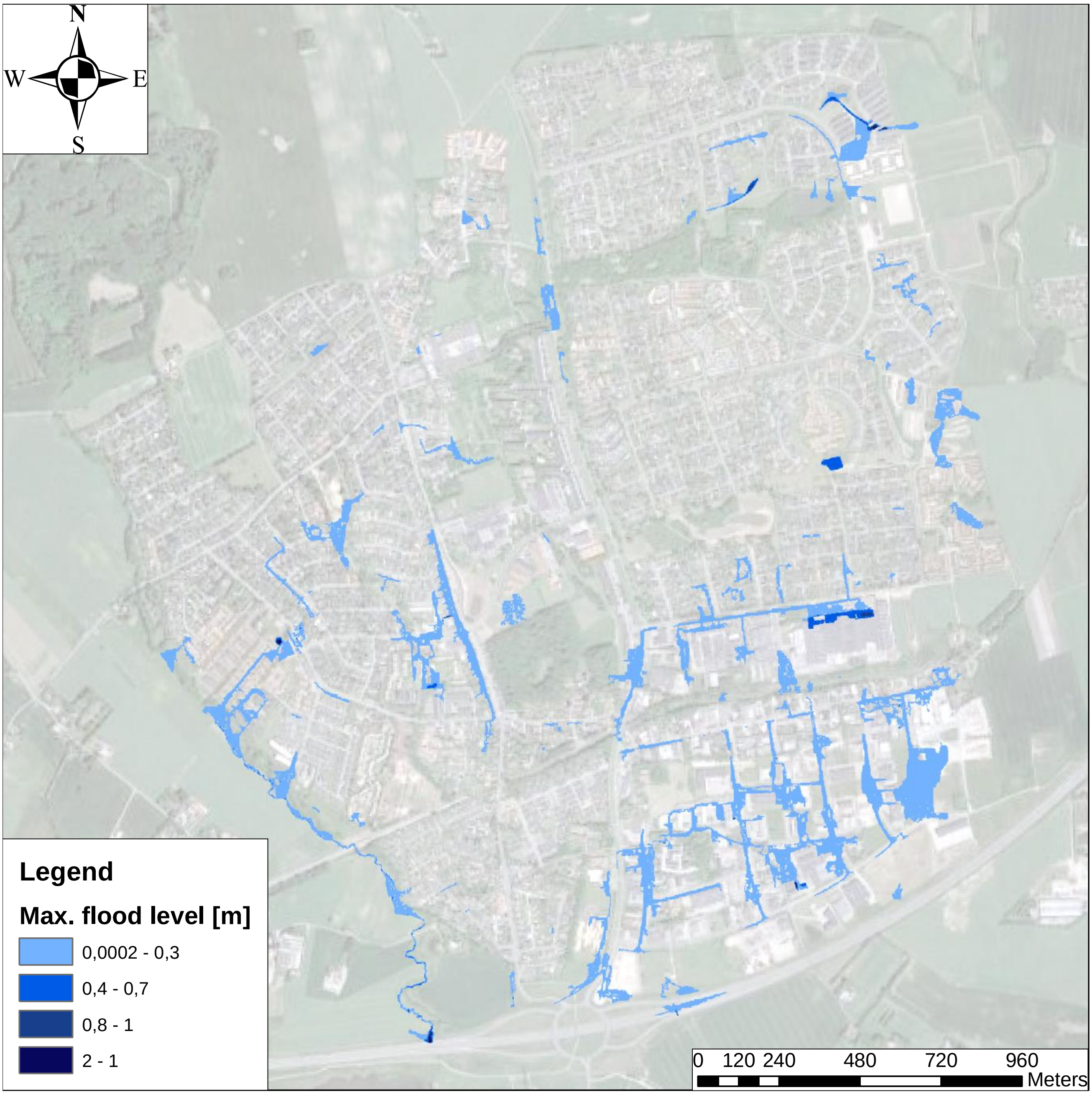

Figure B5: Maximum flood level on 1 August 2006

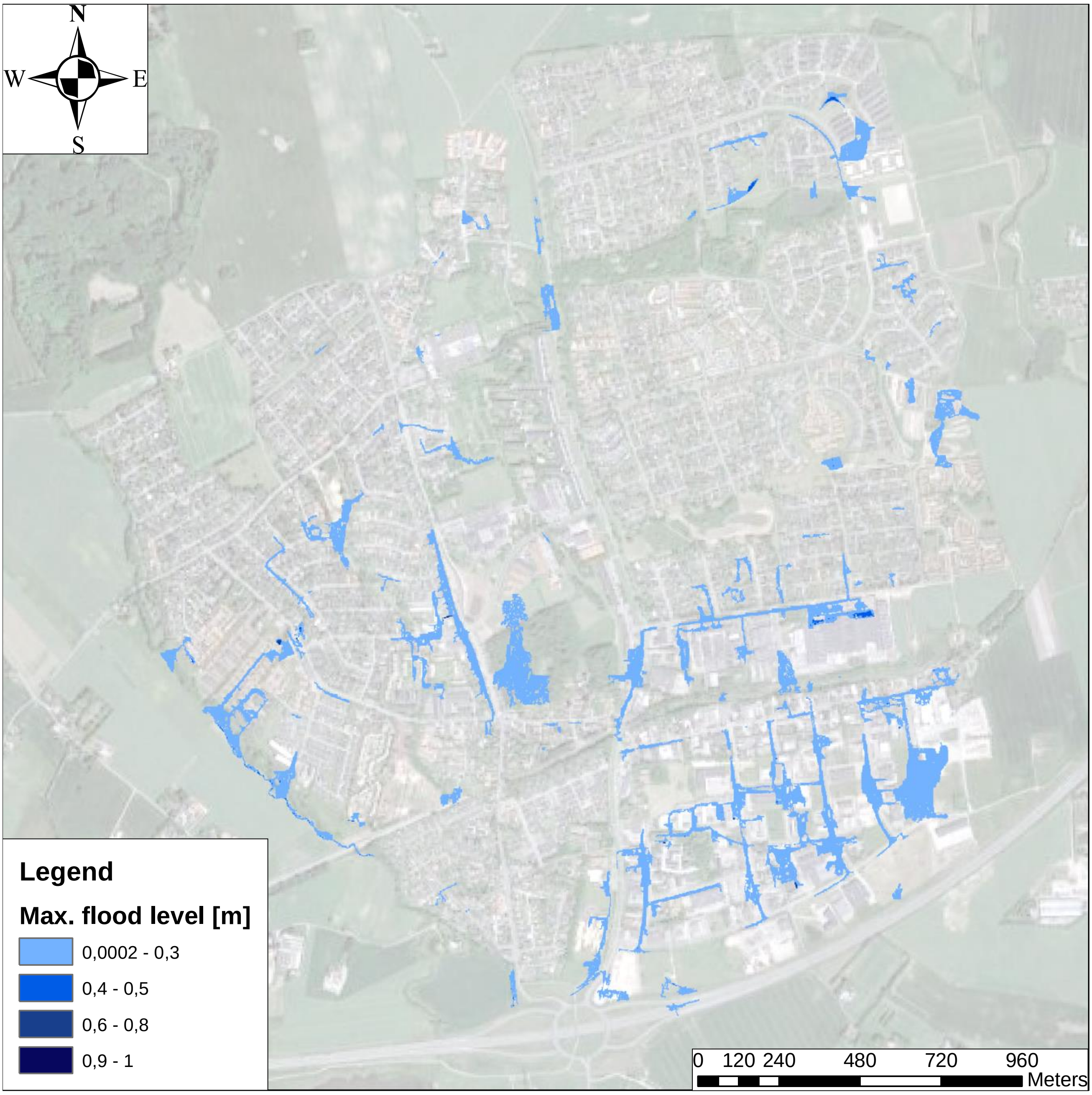

Figure B6: Maximum flood level on 12 August 2006

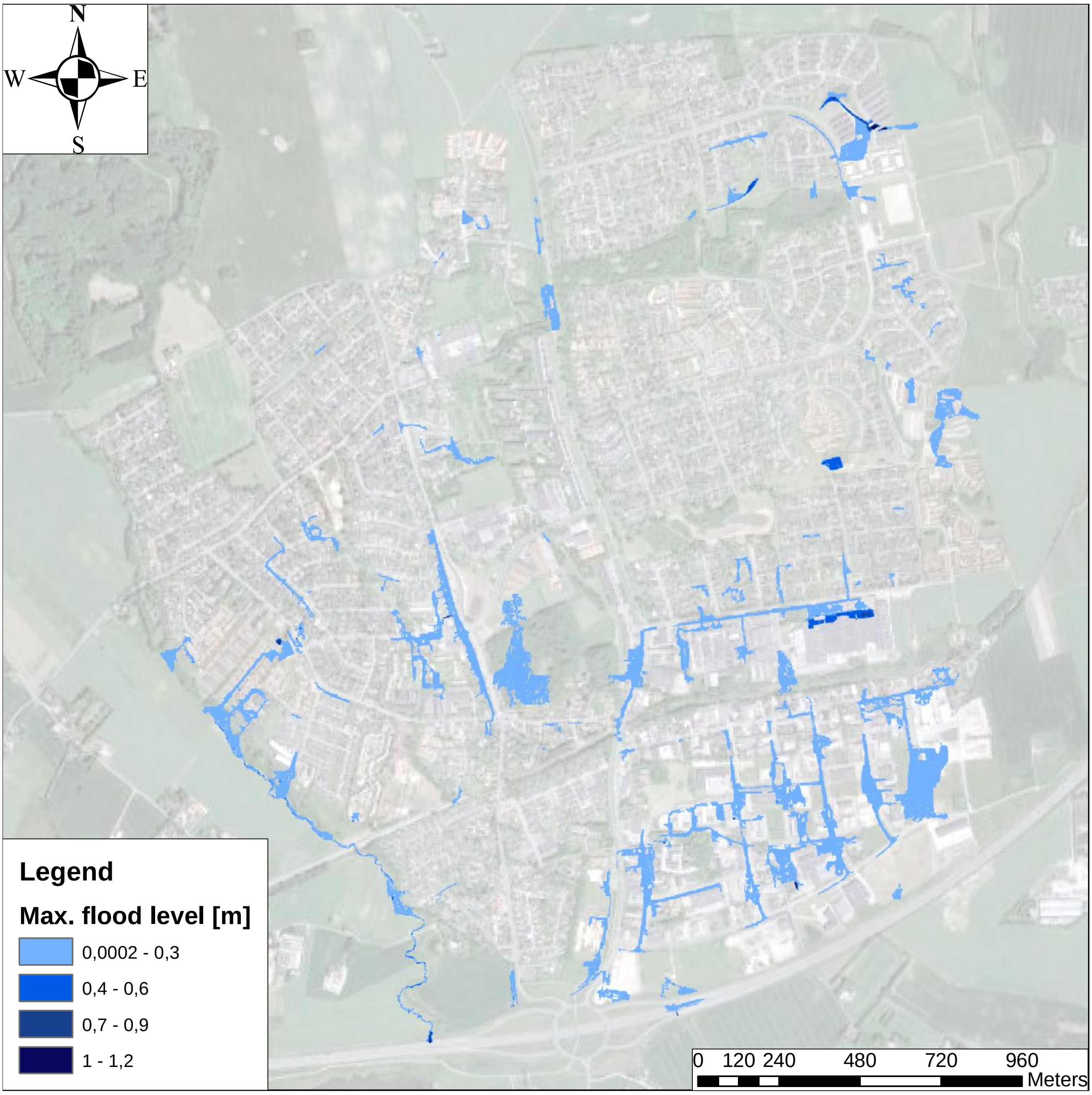

Figure B7: Maximum flood level on 25June 2007

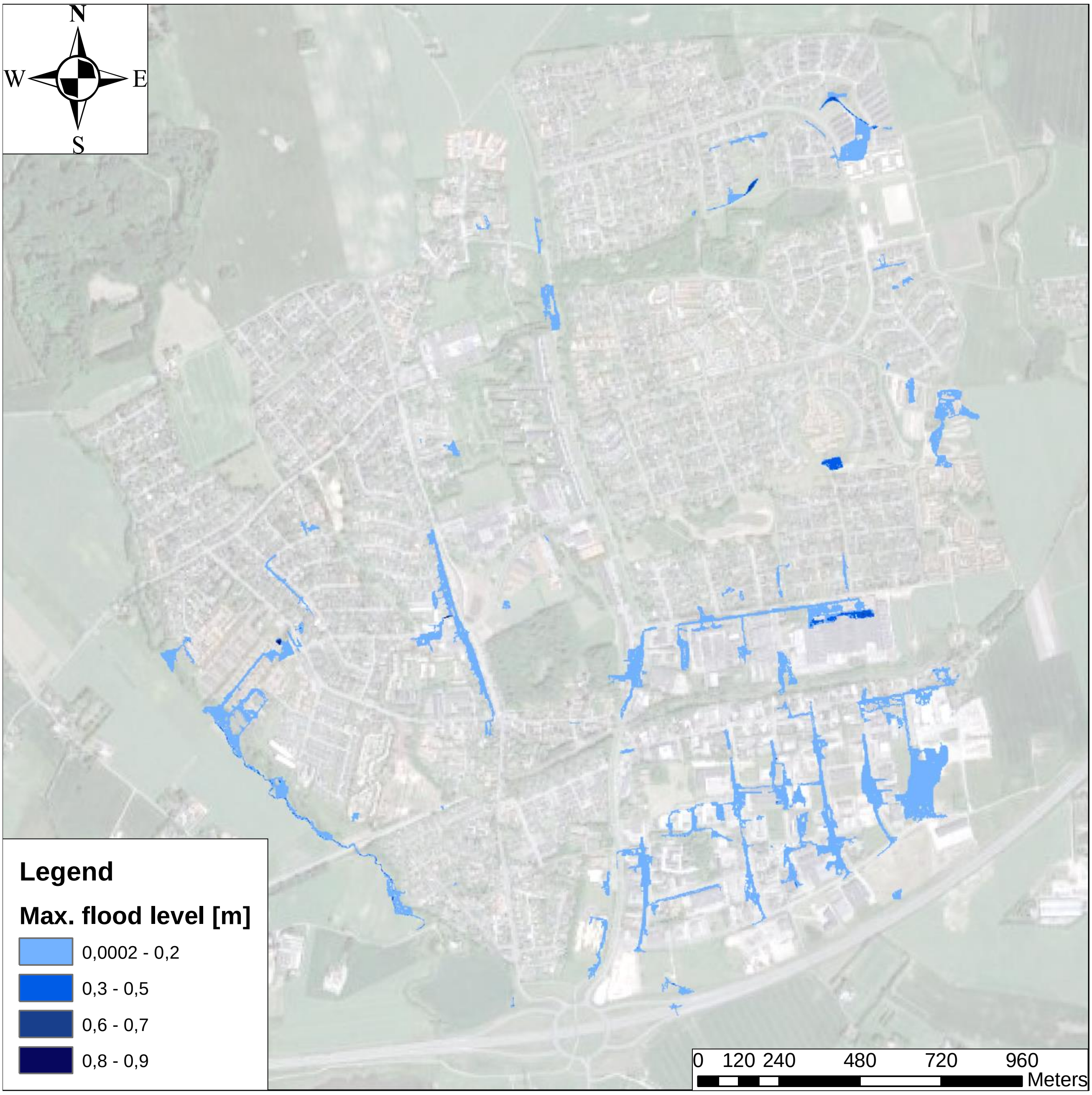

Figure B8: Maximum flood level on 22 August 2012

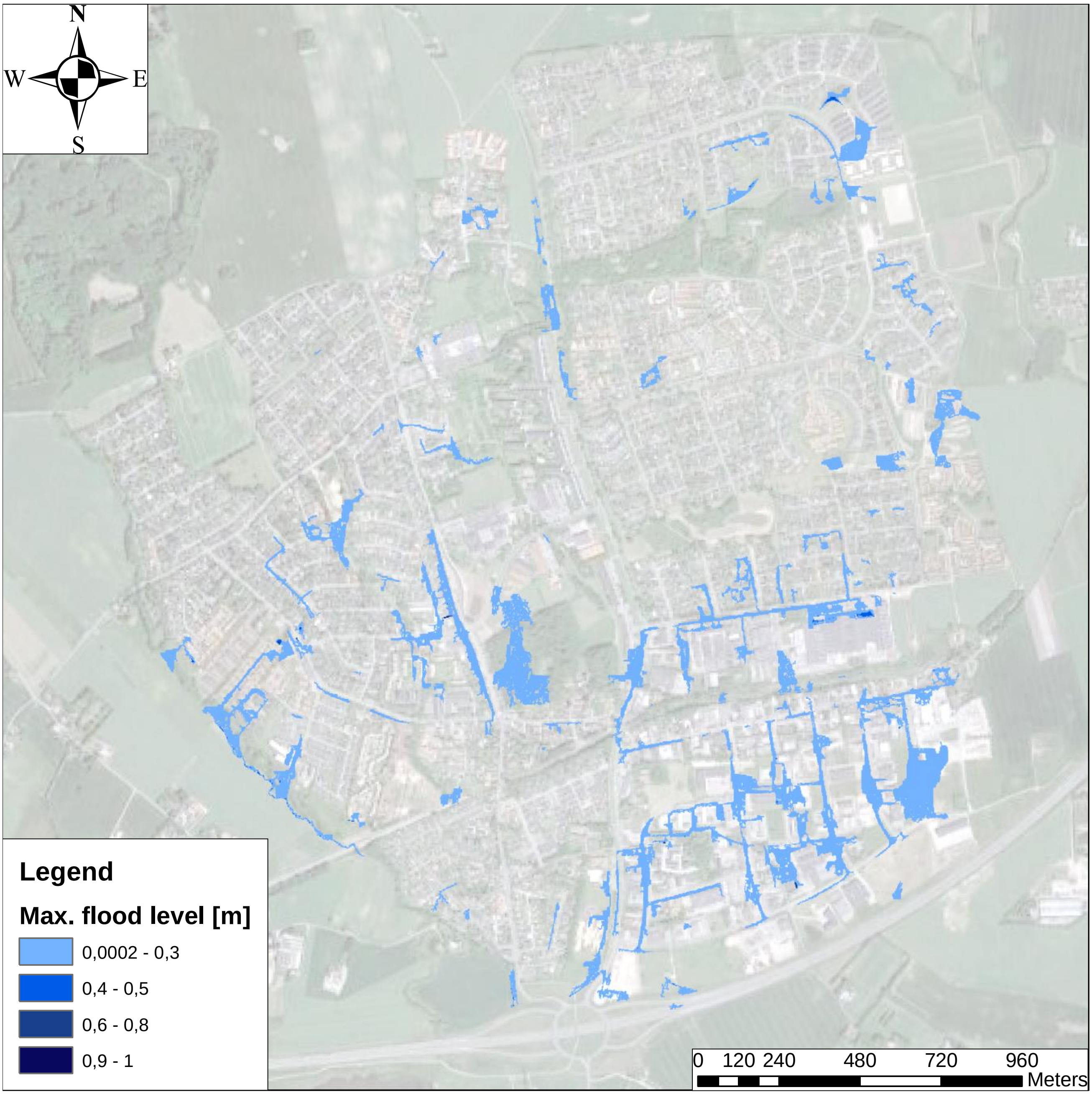

Figure B9: Maximum flood level on 5 May 2015