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How variations of the duration and time to peak of the Chicago Design Storm affect the hydraulic response, as well as the areas contributing to peak runoff, of a synthetic urban catchment area

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Abstract

With an expanding urbanization in the world, and thus the expansion of impermeable surfaces, the risk of pluvial floods is an increasing factor that needs to be considered. This, in combination with increasing rain intensities and frequency of rain events indicates a problem both today and for the future. With this in mind, it is an advantage to increase the knowledge of how different variations of extreme rainfall affects the hydraulic response of urban catchments, as well as which areas in urban environments contribute to the flood peak.

The aims of this study are, with a particle tracking approach, to investigate how the peak runoff contributing areas differ geographically depending on the duration and time to peak of the rainfall event. This also includes the evaluation of what sizes of urban catchment areas are relevant to include when modelling the hydraulic response of Swedish urban catchment in relation to the characteristics of the hyetograph. The catchment area used in this study is made synthetically to represent a generic Swedish urban catchment with regards to the proportions of hardened surfaces, buildings and low points, as well as the slope of the catchment. Various variants of the Chicago Design Storm were implemented in the model. This included three different durations of 2-, 4- and 6 hours of which each, separately, constituted of three different time to peak that is decided by an r-value when creating the design storms. The r-values used in this study is 0.1, 0.4 and 0.8 where the values correlates to an early-, centred- and late peak of the hyetograph. To be able to investigate the peak contributing area, a particle tracking approach was initially used as an equivalent to tracers where the particles are first evenly distributed over the catchment area to then be concentrated to the locations that shows a variation in in the peak contributing area. This was done by using the modelling program MIKE 21 Flow Model FM powered by DHI, which also was used to run the hydrodynamic simulations of the inundation.

The results of the hydrodynamic simulations showed that the rain events generated more runoff as the duration was extended. In addition, the timing of the peak of the rainfall intensity also had an impact on the result as the runoff increased with increasing r-value. Thus, as the peak of the hyetograph is delayed, it imposes an increasing risk of severe flooding. Furthermore, with the use of particle tracking, it could be concluded that the different design storm had an influence on the peak contributing distance where the distance grew larger when the duration of the rainfall event was extended and when the peak of the storm was delayed.

Key words: Catchment area, flood modelling, peak contributing area, hydrograph, hyetograph, MIKE 21, rain intensity, CDS-rain, Chicago Design Storm

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Referat

Med en ökande urbanisering i världen, och med det även en ökning av hårdgjorda ytor, är risken för pluviala översvämningar en allt större faktor som måste beaktas. Detta i kombination med en ökande regnintensitet samt nederbördsfrekvens indikerar ett problem både för idag och för framtiden. Med detta i åtanke är det en fördel att öka kunskapen om hur olika variationer av extrem nederbörd påverkar den hydrauliska responsen i urbana avrinningsområden, samt vilka områden i stadsmiljöer som bidrar till den maximala översvämningen. Syftet med denna studie är att, med hjälp av partikelspårning, undersöka hur peak-bidragande områden skiljer sig geografiskt beroende på regnets varaktighet samt tid till regnintensitetsmaximum. I detta ingår även utvärdering av vilka storlekar av urbana avrinningsområden som är relevanta att inkludera vid modellering av den hydrauliska responsen i förhållande till hyetografens egenskaper.

Avrinningsområdet som används i denna studie är syntetiskt gjort för att representera ett generiskt svenskt urbant avrinningsområde med avseende på andelen hårdgjorda ytor, byggnader och lågpunkter, samt avrinningsområdets lutning. För att studera nederbördens inverkan på den hydrauliska responsen i avrinningsområdet implementerades olika varianter av en designstorm kallad Chicago Design Storm. Detta inkluderade tre olika varaktigheter på 2-, 4- och 6 timmar av vilka var och en, separat, bestod av tre olika tid till regnintensitetsmaximum, vilket bestäms av ett r-värde vid skapandet av designstormarna. De r-värden som används i denna studie är 0.1, 0.4 och 0.8 där det lägre värdet korrelerar med en tidig topp, mittvärdet är lika med en centrerad topp och det högre värdet motsvarar en sen topp på hyetografen. För att kunna undersöka det peak-bidragande området användes initialt en partikelspårningsmetod som en motsvarighet till spårämnen där partiklarna först är jämnt fördelade över avrinningsområdet för att sedan koncentreras till de platser som visar en variation i det peak-bidragande området. Detta gjordes genom att använda modelleringsprogrammet MIKE 21 Flow Model FM som drivs av DHI, vilket också användes för att genomföra de hydrodynamiska simuleringarna av översvämningen.

Det upptäcktes relativt tidigt i simuleringsstadiet av arbetet att det skulle vara svårt att identifiera det peak-bidragande området i avrinningsområdet, då majoriteten av de partiklar som släpptes ut på platser med antingen lågt flöde eller låg vattennivå hade svårt att ta sig till utloppet av avrinningsområdet. Med anledning av detta vändes fokus i studien mot avrinningsområdets centrala dräneringsväg där partiklarna kunde röra sig mer fritt. Därför togs ett beslut att undersöka det peak-bidragande avståndet längs den centrala dräneringsvägen istället för det peak-bidragande området.

Resultaten av de hydrodynamiska simuleringarna visade att regnen genererade mer avrinning när varaktigheten förlängdes. Dessutom hade tidpunkten för toppen av nederbördsintensiteten också en inverkan på resultatet då avrinningen ökade med ökande r-värde. Allteftersom toppen av hyetografen senareläggs, medför den en ökande risk för allvarliga översvämningar. Vidare, med användningen av partikelspårning, gick det att dra slutsatsen att de olika designstormarna hade en effekt på det peak-bidragande avståndet, då avståndet blev större när varaktigheten av regnen förlängdes och när regnets intensitetstopp inträffade senare under regneventet.

Nyckelord: Avrinningsområde, översvämningsmodellering, peak-bidragande område, hydrograf, hyetograf, MIKE 21, regnintensitet, CDS-regn, Chicago Design Storm

Preface

This study is a master´s thesis of 30 credits that finalizes the Master´s Programme of Environmental and Water engineering at Uppsala University and the Swedish University of Agricultural Science. It has been conducted in collaboration with Tyréns, where Johan Kjellin has been supervising with the help of Max Stefansson. Benjamin Fischer has been the subject reader and Antonio Segalini examiner, both at the department of Earth Sciences, Program for Air, Water and Landscape Sciences, Uppsala University.

I would like to direct a special thanks to Johan Kjellin and Max Stefansson at Tyréns for your input and guidance throughout this project. Thanks to Benjamin Fischer for all your advice as subject reader and to Sten Blomgren at DHI for providing me with a software license for MIKE 21. I would also like to thank my fellow master´s thesis-colleagues for the good company and constructive discussions. Finally, I would like to thank all my friends and family for their support during this project and throughout my education.

Populärvetenskaplig sammanfattning

När städer byggs ut så ökar ofta mängden hårdgjorda ytor så som vägar, hus och trottoarer vilket inte släpper igenom något vatten i samma grad som exempelvis gräsbeklädda ytor. Detta i kombination med fler och mer kraftfulla regnoväder kommer leda till att översvämningar inom städer ökar både i antal och allvarlighetsgrad. Med anledning av detta är det bra att utöka kunskapen om vilka konsekvenser som olika utformningar av regn har på översvämningar inom en stad samt om olika områden inom en stad bidrar olika mycket till översvämningen beroende på hur regnet ser ut. För att ta reda på detta används en partikelspårningsmetod som har som syfte att följa vattnets resväg inom ett avrinningsområde för att då avgöra hur områden som bidrar till maximal översvämning varierar geografiskt vid tillsättning av olika längder på regn samt tid till dess toppintensitet. Utöver detta undersöktes det om det går att avgöra vilka storlekar på avrinningsområden, i förhållande till regnets egenskaper, som är rimliga att inkludera vid modellering av översvämningar inom städer.

Avrinningsområdet som används i denna studie är skapat för att efterlikna ett genomsnittligt svenskt urbant avrinningsområde med avseende på andelen hårdgjorda ytor, byggnader och lågpunkter, samt avrinningsområdets lutning. För att undersöka hur regnets variationer påverkar översvämningsgraden så användes olika varianter av ett simulerat regn som kallas Chicago Design Storm (CDS). Detta inkluderade CDS-regn med de tidsmässiga varaktigheterna: 2-, 4- och 6 timmar vilket även inkluderade regn med olika tidpunkter vid regnets maxintensitet.

Tidpunkten för när regnets maxintensitet inträffar styrs av ett r-värde som kan variera mellan 0 och 1. I denna studie används r-värdena: 0,1, 0,4 samt 0,8 där ett lågt r-värde ger en tidig intensitetstopp, medan ett högt r-värde ger en sen intensitetstopp tidsmässigt. För att avgöra vilka områden inom avrinningsområdet som bidrar till maximal översvämning användes en partikelspårningsmetod som då agerade som ett spårämne. Partiklarna placerades till en början jämnt över hela avrinningsområdet, men för att sedan koncentreras till de platser som påvisade en variation i bidraget till översvämningen. Detta gjordes genom att använda modelleringsprogrammet MIKE 21 Flow Model FM som drivs av DHI, vilket också användes för att genomföra skyfallssimuleringarna. Relativt tidigt i simuleringsstadiet stod det klart att det skulle vara svårt att identifiera de ytor i avrinningsområdet som bidrar till översvämningstoppen, då majoriteten av de partiklar som släpptes ut på platser med antingen lågt flöde eller låg vattennivå hade svårt att ta sig till utloppet av avrinningsområdet. Med anledning av detta vändes fokus i studien mot avrinningsområdets centrala delar där partiklarna kunde röra sig mer fritt. Därför togs ett beslut att undersöka det peak-bidragande avståndet längs den centrala dräneringsvägen i stället för det peak-bidragande området.

Resultaten av skyfallssimuleringarna visade på att avrinningen ökar när regnet förlängdes tidsmässigt. Utöver detta spelade det roll vilken tidpunkt som toppen av nederbördsintensiteten inträffade då mängden vatten som blev till avrinning ökade i takt med att toppen för nederbördsintensiteten för regnet inträffade senare tidsmässigt. Fortsättningsvis så visade partikelspårningen att de olika designstormarna hade en effekt på det peak-bidragande avståndet i och med att avståndet som partiklarna färdades till utloppet, och därmed bidrog till översvämningstoppen, blev större när regnets längd utökades och när regnets maximala intensitet inträffade senare i händelseförloppet.

Contents

1 Introduction

Floods and cloudbursts seem to be an increasingly common factor for people all around the world (Berghuijs et al. 2017). Sweden is no exception and has, only in the recent years, been affected by several extreme cloudbursts which consequently has led to extensive floods (Hernebring & Mårtensson 2013). Since modern day designs of urban areas often have a considerable amount of impermeable hardened surfaces, it is of great importance that the sewage systems have the capacity to manage to drain the surplus of water. Thus, if not, it can lead to a deteriorated water quality and, furthermore, severe repair- and decontamination costs. Due to this issue, it is of high interest to improve the predictions of the consequences of heavy cloudbursts so that floods can be prevented better in the future. In addition, this includes increasing the knowledge regarding how these cloudbursts should be represented within a model, and what characteristics of the runoff area affect the hydraulic response of the catchment.

Furthermore, within hydrology, it is of interest to know where, geographically, the water comes from to evaluate the design of catchment areas. In practice, this is commonly carried out with the use of tracers, which can be placed at strategic points within the catchment. The tracer then follows the streamflow of water, thus, the pathway can then be evaluated at a point by the outlet of the catchment. With this technique it is possible to use several different types of tracers, such as the stable isotope O18 or fluorescent tracers, depending on the purpose of the project and the conditions of the location.

When modelling floods, it is possible to obtain various assessment parameters depending on the aim of the study. However, one aspect that is more complicated to evaluate is which parts of catchment areas are contributing to the peak runoff and how the water travels to the outlet of an urban catchment area. One issue that has been brought up by Elfström & Stefansson (2021) concerning the contributing area is that, when the catchment size is larger than the area contributing to the flood peak, the size of the catchment area ceases to matter. In addition, it is likely that there will be incorrect assumptions about how the hydraulic effect is affected by the size of the catchment area when creating synthetic models of urban catchment areas. In this study, the synthetic model is made artificially, and is created to resemble a real Swedish urban catchment.

The contributing area can be described as a partial area within a catchment that generates runoff to the outlet (Betson & Marius 1969). Furthermore, the contributing area can also be considered as the areas that are generating the peak runoff at the outlet of the catchment, thus, it is the origin area of the water which is presented from the beginning of a hydrograph to the centre of its peak (Fiorentino et al. 2007). According to Beven & Kirkby (1979), subsurface flow is transporting water too slowly to be a contributor to the peak of the hydrograph; hence, only overland flow is considered and examined in this project. The reason why the contribution area can differ within a catchment area is that it is dependent on the characteristics of the surface. A surface with low permeability and a high Manning’s number tends to generate more runoff. Hence, the probability of it contributing to the flood peak increases (Beven & Wood 1983).

Design storm events is a common approach when evaluating stormwater runoff and dimensioning sewage systems (Watt & Marsalek 2013). There are two methods when creating a design storm, using a methodology based on a synthetic rain event or making use of observed historical precipitation data. Furthermore, when applying either of the concepts, a hyetograph must be made to be used as an input parameter in a runoff model.

It is common to use a six-hour rain event called Chicago Design Storm, with a centred peak, when modelling the effect of rainfall (Rivard 1996). However, it is not entirely obvious if it is always the best alternative to use depending on the size and characteristics of the catchment area. Hence, the simulations will use the Chicago Design Storm with three varied rain durations, combined with three different distances to peak, to be able to distinguish whether the designed storms have a significant effect on the hydraulic result.

The simulations are performed using the software MIKE 21 Flow model FM which is powered by DHI. The software can execute advanced hydrodynamic calculations which this study will benefit from when simulating the different design storms. In addition, since a tracer approach is set to be used in this project, there is a module within the Flow Model FM called particle tracking, also developed by DHI, that is most suitable for the purpose. The particle tracking module allows the user to freely place sources of the particles inside a boundary area. These particles can then follow the same path as the water in their surroundings with the use of the hydrodynamic calculations. Together with the variations of the design storm, the particle tracking approach will be used to identify and evaluate the areas that contribute to peak runoff.

2 Aim and objectives

The purpose of this study is to investigate the potential relationship between rain duration, and time to maximal rainfall intensity, with the peak-contributing area with the use of particle tracking. Furthermore, following research questions are to be answered throughout the thesis:

- Do areas that contribute to peak runoff, within an urban catchment, differ geographically depending on duration and time to peak of the Chicago design storm.
- Can the previous question be determined by examining the travel times from the investigated areas?
- By evaluating the peak runoff contributing area, is it possible to distinguish what sizes of catchment areas that are relevant to include when modelling urban catchment areas depending on the characteristics of the hyetograph?
- Is the particle tracking approach a reasonable way of evaluating the peak runoff contributing area, and can it be a new concept to use when modelling inundation?

3 Theory

3.1 Different types of rain

Precipitation is generated in various ways, one of them is the orographic rain which is formed when wind currents are pushed up over natural heights, such as mountains. At this state, the relatively warm air is quickly cooled down, and then condensed, by the ascent. Consequently, this leads to precipitation on the side of the mountain which is facing the wind (Hendriks 2010). Convective rain, on the other hand, depends on the vertical ascent of unstable layered air due to a rapid warming process when the ground is heated by the sun. This event is more common during the summer when the average temperature is usually the highest of the year and often results in heavy cloudburst (Hammarstrand 2021). The size of the convective rain cells varies but can in some cases reach a radius of up to 10 km (Hammarstrand 2021).

3.2 Pluvial and fluvial flooding

Inundation can be classified in two main categories: pluvial and fluvial flooding. What distinguishes the two variants from one another is that the pluvial flooding only accounts for the overflow, generated by rainfall, before reaching a drainage system or watercourse (Falconer et al. 2009). In addition, pluvial flooding is separated from the event, often referred to as flash floods, as the latter generally originates from rising water levels in watercourses due to heavy rainfall (Falconer et al. 2009).
In contrast to pluvial flooding, fluvial flooding is caused by water levels exceeding the max capacity of watercourses, such as rivers or streams, which can lead to the collapse of dikes which, ultimately, can cause large flood areas (Tanaka et al. 2020).

3.3 Infiltration rate

Within a catchment area, there can be considerable variations of the infiltration capacity depending on several various parameters. The infiltration capacity is determined by whether the soil is coarse-grained or fine-grained, what type of vegetation is present, soil water content at the beginning of rainfall, precipitation rate and duration of the rainfall event.

The infiltration capacity is typically higher for coarse-grained soils which often contain a significant amount of sand and gravel. Furthermore, this leads to a more permeable soil which allows the water to infiltrate. Hence, the cavities within the soil are more extensive than fine-grained soils such as clay or silt. The soils that are more fine-grained tend to contain more water since it binds water both capillary and adhesive to its pores, resulting in the soil being less permeable.

3.4 Saturated soil

Depending on the level of sub surface saturation, the infiltration capacity of the soil will vary. Hence, when the rainfall intensity is greater than the infiltration capacity, it can lead to a more intense runoff event since less water is absorbed, thus, it continues to flow within the catchment. Furthermore, soil saturation is the definition of soil moisture content which is an important factor when examining runoff, considering that when a soil is saturated the infiltration rate is near zero (Grip et al. 1994). Consequently, in this scenario, almost all of the rainfall contributes to the pluvial flooding.

3.5 Manning's formula

Since the surfaces have different properties, the water's ability to flow differs depending on the roughness of the various materials on the ground. Moreover, to calculate the velocity of water over a certain surface a factor called Manning's number ($m^{1/3}/s$), referred to as M is used. According to Gustafsson & Mårtensson (2014), it is appropriate to use a manning´s number of 50 $m^{1/3}/s$ for a hardened surface and 2 $m^{1/3}/s$ for grass surfaces, which is later used when modelling the catchment area.

Manning's number can then be used to calculate the water's velocity on different surfaces through Manning's formula, which is presented in equation 1.

$$v = M \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \quad (1)$$

Where v is the velocity, M is Manning's number ($m^{1/3}/s$), R is the hydraulic radius (m), which is obtained by dividing the area of the cross section with the wetted perimeter, and S is the slope (Venutelli 2005).

3.6 Runoff coefficient

The share amount of water that forms runoff, after losses such as evaporation, infiltration and uptake from plants, is expressed as the runoff coefficient, φ (Svenskt vatten 2011). This is used to calculate the runoff from different surfaces with regards to the rainfall intensity (Goel 2011). Consequently, a reduced rainfall intensity is produced, which can be seen in equation 2.

$$i_{red} = \varphi \cdot i \quad (2)$$

Where i_{red} is the reduced rain intensity, φ is the runoff coefficient and i is the rainfall intensity.

3.7 Hyetographs and hydrographs

A hyetograph is used to, graphically, present a rain´s intensity distribution, in relation to time (Svenskt vatten 2011). However, a hydrograph represents the discharge of water through a specified cross section in relation to time (Rogers 1972).

3.8 Intensity-duration-frequency curve

The IDF-curve is based on statistics of block rains, which can be defined as the largest mean value of the rain intensity during a specific time frame of a rain event (Hernebring 2006). The underlying data is gathered from statistics of historical rain events and the mean intensities are distributed in relation to their return period and temporal duration (Svenskt vatten 2011).
However, the IDF-curves were originally calculated by Dahlström (2010), with the use of equation 3.

$$i_{Å} = 190 \cdot \sqrt[3]{Å} \cdot \frac{\ln(T_R)}{T_R^{0,98}} + 2 \quad (3)$$

Where $i_{Å}$ is the rain intensity (l/s), T_R is the duration of the rain (minutes) and Å the return period (months).

3.8.1 Chicago Design Storm

One design storm based on the IDF-curve is the Chicago design storm, made by Keifer & Chu (1957), which is referred to as CDS in this thesis. The CDS is constructed through two equations which calculate the rain intensity before and after the maximum intensity. The essential variables of the equations are taken directly from the IDF-curve, which represents Swedish conditions. However, many studies have been conducted within this subject, some of them have come to the conclusion that when using design storms such as the Chicago Design Storm (CDS), it can lead to an exaggeration of the hydraulic response compared to reality (Watt & Marsalek 2013). This is because the hyetograph of the CDS is very much concentrated at the peak of the rain intensity, which with a 100-year return period results in a tremendous cloudburst. However, the CDS includes the maximum intensity of every return period up to 100-year rains which can be an advantage as it is then possible to extract information of different return periods from one rain event (Watt & Marsalek 2013).

The different variations of the CDS can be constructed through the two equations 4 and 5.

$$i = \frac{a \cdot b}{\left(\frac{|t-rT|}{r}+b\right)^2} + c \qquad (4)$$

Where equation 4 calculates the hyetograph before the maximum rain intensity.

$$i = \frac{a \cdot b}{\left(\frac{|t-rT|}{1-r}+b\right)^2} + c \qquad (5)$$

Moreover, equation 5 is calculating the hyetograph subsequent to the maximum intensity.
What distinguishes the two equations is the denominator which includes “1-r” in equation 5 instead of “r” in equation 4. The time to peak ratio, preceding, the peak intensity of the design storm is referred to as the r-value and ranges between 0 and 1 (Marsalek 1980). In addition, the r-value is the ratio of when the peak rainfall intensity occurs in relation to the entire rainfall duration (Pan et al. 2017).
Also, according to Marsalek (1980), design storms with r-values closer to 1 results in larger runoff than design storms with the same rain intensity but lower r-values. Furthermore, Marsalek (1980) argues that this is due to the storage capacity of catchments usually is at its highest at the beginning of the storm. Thus, when the peak of the rain event is relatively late, the storage capacity has decreased significantly by the time the rain is at maximum intensity.
The variables of a, b and c are parameters that describes the local conditions and are decided by the intensity-duration-frequency curve (Yang et al. 2020). An example of the CDS-hyetograph can be seen in figure 1, where it is also pointed out from which side of the hyetograph that the r-values is used for equation 4 and 5.

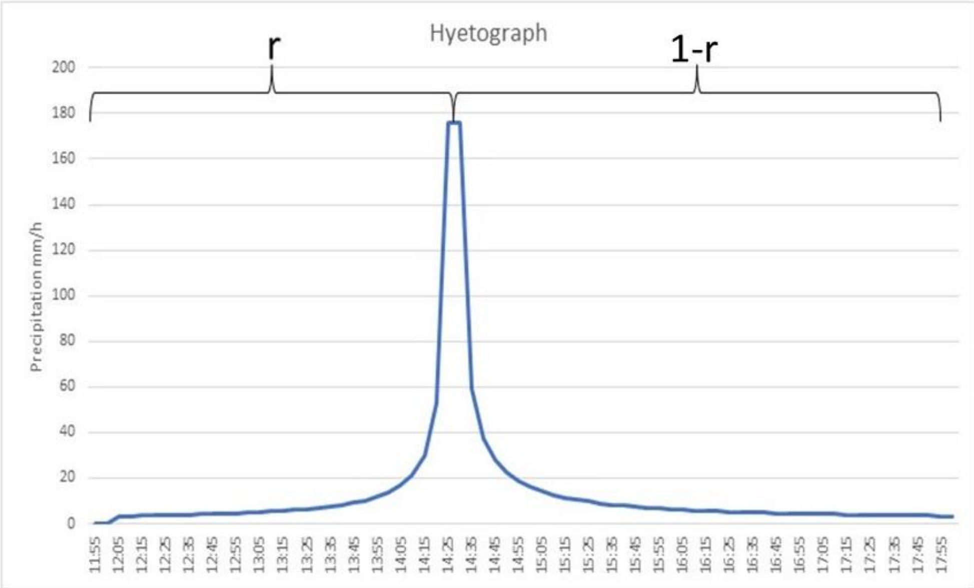

Figure 1: Example of a hyetograph with a duration of six hours which is based on the Chicago Design Storm-concept. The r-values shown in the figure describes what side of the hyetograph that is calculated by equation 4 and 5.

3.9 Earlier studies

Previously, studies have been conducted to evaluate the effect on inundation from various variants of a CDS. For instance, an implementation of three sets of variants including a modification of the return time, duration time and time to peak resulted in assorted results between the different variables (Qin et al. 2013)**.** Qin et al. (2013) focused on analysing the impact of the alternative CDS-rains, parameters such as flood volume, accumulated rain at both the beginning and the end of the rainfall, peak amount rainfall, surface infiltration and drainage pipe discharge.

Firstly, seven different return periods of 1-, 2-, 5, 10-, 20-, 50- and 100-years were included, which, consequently, resulted in an increase of flood volume as the return period got longer. In addition, with a longer return period, the accumulated rainfall amount in the beginning of the event decreased but the amount at the end increased. This resulted in an increase of peak rainfall amount since it is calculated by subtracting the accumulated rainfall at the end with the accumulated amount of rainfall at the beginning.
Moreover, parameters such as discharge via drainage pipes and soil infiltration both decreased with increased rain intensity which ultimately led to an increase in flood volume.

Group two included seven different durations of the storm event, 1-, 1.5-, 2-, 2.5-, 3-, 3.5- and 4 hours. Although, it should be mentioned that Qin et al. (2013) used a decreasing intensity at the peak of the rainfall in combination with extending the duration. Accordingly, it resulted in a decrease of flood volume as the duration was extended. Furthermore, as the duration increased, the accumulated rainfall in the beginning increased and decreased by the end. Thus, it led to a decrease of the peak amount of the rainfall. However, the drainage discharge and soil infiltration also decreased which contributed to the decrease of flood volume.

Lastly, group three included nine different values of the time to peak ratio, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9. The results showed that with an increase of the ratio, the intensity of the rainfall in both the initial- and later part of the rain event decreased. Thus, leading to an increase of accumulated rainfall amount in the beginning and the end of the rainfall. In addition, the results indicated that when the time to peak ratio was below 0.8, the peak amount of rainfall increased. However, values of the time to peak ratio above 0.8 resulted in a decrease of peak rainfall amount, since the accumulated rainfall amount in the beginning of the rain event increased more than the accumulated rainfall by the end of the event. Moreover, the rising ratios had only a slight effect on the drainage pipe discharge and soil infiltration, hence, the flood volume increased as the ratio got higher, although the increase began to stagnate at a time to peak ratio of 0.7

Within the field of hydrology, contributing areas have been a relevant factor for a long period of time: as for example Dunne (1983) mentioned the importance of having knowledge of how the contributing area affects the storm hydrograph. The theory was that the contributing area acted differently under various parameter circumstances such as the size of the rainstorms, soil conditions and hillslope gradient. According to Dunne (1983), it was important to include the impact of a varied contributing area when creating spatially distributed runoff models. However, Beven & Kirkby (1979) argued in a study regarding variable contributing areas that the overland excess flow could be more significant for smaller catchments. Although, according to Beven & Kirkby (1979), the overland excess flow is less substantial for larger catchment areas, hence, the contributing areas are more concentrated to the vicinity of the channels.

When examining areas within a catchment that contributes to peak runoff, previous studies have primarily used theoretically derived models. One example is a study made by Fiorentino et al. (2007)**,** where they implemented the contributing area as a stochastic variable in a probability density function. The results of the study implied that the probability density approach was fairly successful by estimating the size of the contributing area, although the focus of the study was mainly related to the impact the soil properties had on the contributing area and had a limited focus on the rainfall characteristics.

Contributing areas has also been discussed in relation to variable source areas. For instance, Buchanan et al. (2012) discusses the term variable source areas, which is based on the theory that an area’s runoff generation can vary seasonally as well as during a storm due to changes in saturation. Hence, Buchanan et al. (2012) argues that areas contribute to the generated runoff differently depending on the length of the rain event and the conditions regarding the saturation of the soil throughout the investigated event. The model used in the mentioned study was a Spatially Distributed Direct Runoff Model which used similar calculations to calculate the flow of water as in this study. In addition, the flow that passes each grid cell is calculated separately which consequently makes it possible to use runoff-routing to evaluate the path of the water. The study could conclude that the runoff generating areas were concentrated along the stream network and extended into the landscape as the rainfall continued.

4 Method

4.1 Modeling with MIKE

4.1.1 MIKE Zero

MIKE Zero is a software which includes various modules for different modelling uses and it provides a graphical user interface (GUI) where new, and existing, projects can be started. Furthermore, in this project, the module used is the MIKE 21 Flow Model FM, based on a flexible mesh technique, whose main purpose is to model environments such as oceanographic, coastal and estuarine. However, it is still possible to use the module when modelling inland flooding.

4.1.2 MIKE 21 Hydrodynamic module

The hydrodynamic module, which is included in the Flow model FM, is based on the three-dimensional incompressible Reynolds averaged Navier-Stokes equations, thus being able to derive the mass and momentum preservation of water through the shallow water equations which then can be used to calculate the flow of water (DHI 2017a).

4.1.3 Urban catchment

The catchment area, which originally was created by Elfström & Stefansson (2021), is implemented in MIKE 21 as a bathymetry grid file which includes the topography and the height of buildings within the urban area. Other input parameters such as infiltration and surface roughness are included in the model as separate input files.
The model is built to be able to represent an urban catchment for an average Swedish city with the highest point at 124 m above sea level. The outer limits of the catchment are 8 km x 8 km with the complete area at 64 km^2 as well as grid cells of 10 m x 10 m. The urban catchment as a whole, as well as one of the residence areas can be seen in figure 2.

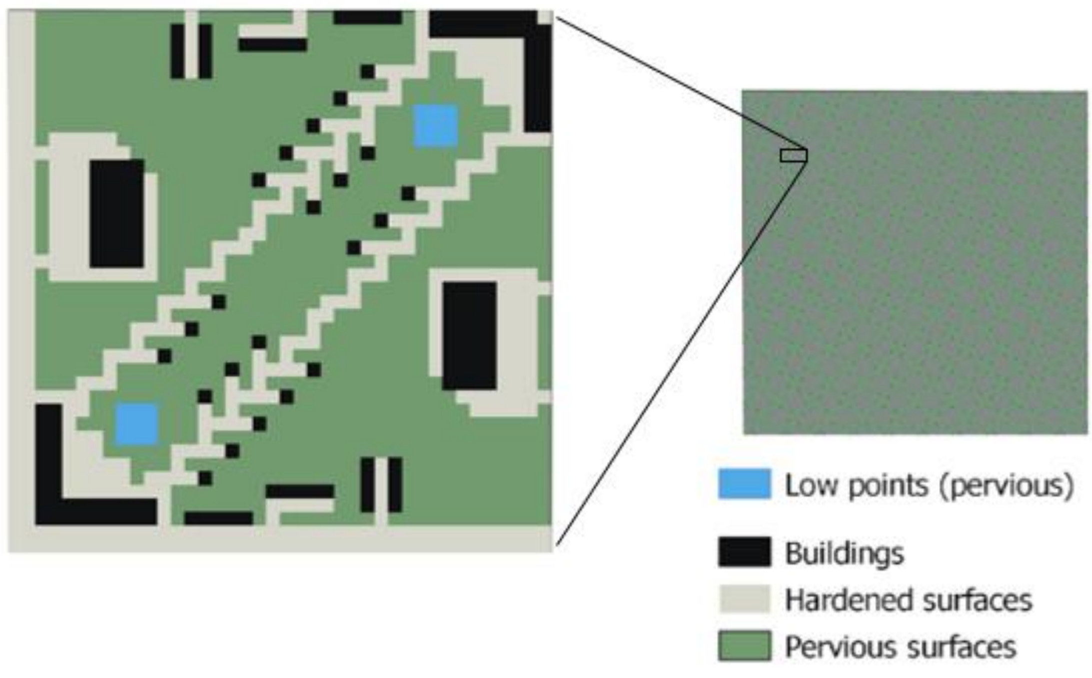

Figure 2: To the left: One of 400 blocks of residence areas in the catchment. To the right: The 400 residence areas combined which forms the urban catchment area.

4.1.4 Bathymetry

The bathymetry is based on the topography of the model and has the same characteristics of a digital elevation model. However, buildings and low points are added to create urban characteristics to the area. Furthermore, the buildings are placed so that they reach three meters above the ground surface and the low points are one meter deep below the surface. The elevation variations of the catchment can be seen as a visualization in figure 3, which is similar to the one used in a previous master´s thesis by Elfström & Stefansson (2021).

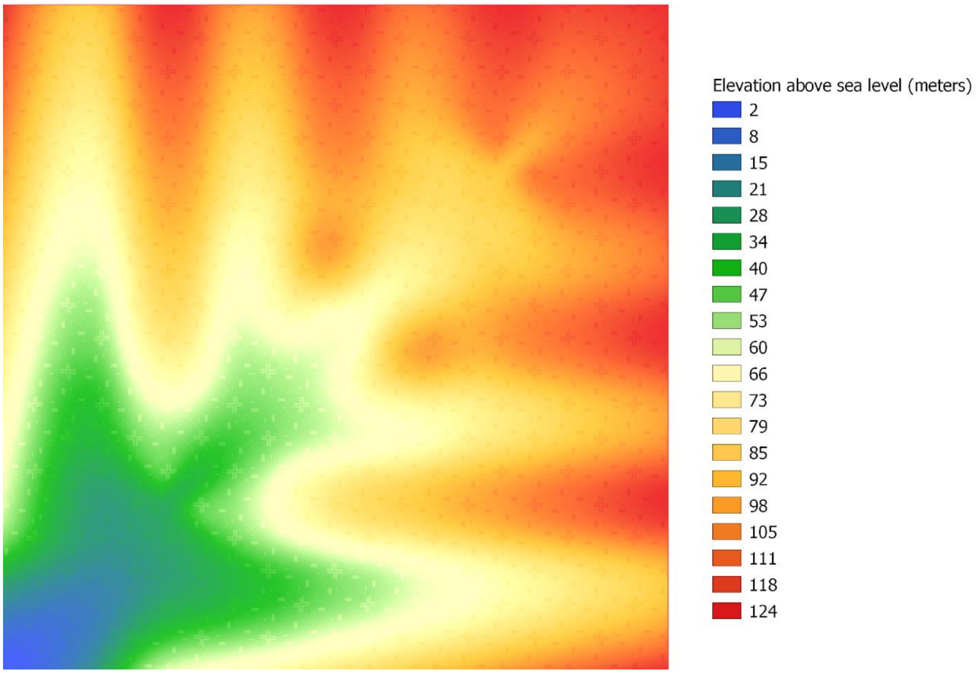

Figure 3: A visualization of the topography of the catchment area

4.1.5 Boundary

The grid cells closest to the surrounding border of the bathymetry is set to be non-penetrable. However, in the lower left corner of the catchment, there is a squared area that extends outside of the main catchment, which has different boundary conditions than the rest of the area. For this sub-area, the boundary is set to be completely permeable at the left and lower side so that the water easily can flow out of the catchment area, thus, reducing the risk of water stagnating by the outlet.

4.1.6 Simulation time

The simulation time might have to be altered depending on the duration of the rain event and the travel time for the water in the catchment so that there is enough time for the simulations to contain both the rain event and the resulting runoff. Multiple simulations must be performed to examine what simulation time is enough for the water within the catchment to create a peak in the outflow hydrograph. This is mostly affected by the slope of the catchment since a greater level difference between the upper part and the lower part of the catchment, consequently, leads to a faster flow to the outlet.

When determining the simulation time, it is important to set a time step so that the simulation is stable (DHI 2017b). This can be evaluated by calculating the courant number C_R for each simulation: for the simulation to be stable, the courant number cannot exceed 1. The equation to calculate the courant number can be seen in equation 6.

$$C_R = c \cdot \frac{\Delta t}{\Delta x} \qquad (6)$$

Where c is the maximum speed of the flow in the model, Δt is the time step and Δx is the grid spacing (DHI 2017b).

4.2 Input parameters

4.2.1 Flood depth

To distinguish whether a grid cell is flooded or not, a drying depth and flood depth has to be decided. The drying depth is the limit where, if below the depth value, the surface is to be considered as dry (DHI 2017b). Furthermore, in this model, the drying depth is set as 0.003 meter. The flood depth on the other hand is used to confirm that the grid cell is flooded if the water level exceeds the specified value, which in this case is set to be 0.008 meter. These values are the same values as used by Elfström & Stefansson (2021). Every grid cell where the water level is above said value should be considered as flooded.

4.2.2 Eddy viscosity

When modelling flowing water, there will be an inevitable turbulence which needs to be considered. This is manageable through the eddy viscosity, which is a quantity that accounts for the turbulence within a model (DHI 2017b). The eddy viscosity can be estimated through equation 7 (DHI u.å.).

$$Constant\ eddy \left[\frac{m^2}{s}\right] = 0{,}02 \cdot \frac{\Delta x \cdot \Delta y}{\Delta t} \qquad (7)$$

Where Δx and Δy is the size of the grid cells at the two different directions in the coordinate system and Δt is the time step of the simulation. Since the length of the sides of the quadratic grid cell is 10 meters and the time step of the simulations is 0.5 s, the constant eddy viscosity is 4 $\frac{m^2}{s}$

4.2.3 Bed resistance

The bed resistance is varied throughout the catchment and depends on the ground's surface material. For instance, there is a difference in resistance whether there is concrete or grass, where the concrete then has a lesser resistance than the grass, thus, resulting in a greater flow speed of the water. The layout of the bed resistance is implemented in the model as an input file which has been created through GIS. The bed resistance, which is related to the Manning formula, in this study is 50 $m^{1/3}/s$ for hardened surfaces and 2 $m^{1/3}/s$ for grass surfaces.

4.2.4 Precipitation

To evaluate how the hydraulic response of the catchment area is affected by cloudbursts, the simulations are performed with different durations of the Chicago Design Storm as well as various temporal distances to the peak of the hyetograph. Based on previous research by Qin et al. (2013) regarding the shape and length of design storms, the durations included in the study are 2h, 4h and 6h. Furthermore, the r-values for the distance to the peak of the rain intensity is 0.1, 0.4 and 0.8, which will reflect rainfall events with an early, centred and late timed peak.

A software which is produced, and also provided, by Tyréns is used to create the varying rain events. The program allows the user to insert parameters such as the chosen return period, duration of the rain event, r-value, time step of the data points and the duration of the peak intensity. When the software has calculated all of the input parameters a time series of the precipitation values are exported as a text file which consequently can be used to implement in the MIKE powered by DHI-software.

4.2.5 Infiltration

The infiltration is varied across the catchment area depending on whether the surface is hardened or not. Thus, the infiltration is regulated by several factors which controls to what extent the soil is susceptible to water percolation, hence, the relevant parameters are infiltration rate, leakage rate, porosity, initial water content and depth (DHI 2017b).
Furthermore, apart from implementing the input file, some settings need to be set for how the infiltration should work when running the simulations. The one that is used in this project is the mode “constant infiltration with capacity”, which describes the water´s movement downwards in the soil profile using physics based on earlier mentioned parameters (DHI 2017b). The available water then travels from the surface to the saturated zone and later continues to move to the saturated zone. The parameters used in this study can be seen in table 1.

Table 1: Infiltration parameters used in the model

Parameters	**Hardened surfaces**	**Grass surfaces**
Infiltration rate	0.001 mm/h	36 mm/h
Porosity	0.01	0.445
Depth of infiltration zone	0.01 m	0.3 m
Leakage rate	0.01 mm/h	0.4 mm/h
Initial wetness conditions	0	58%

4.2.6 Decoupling

In consideration of the fact that the use of the particle tracking module, to evaluate peak contributing areas, is a relatively unproven method, it is highly likely that there is a need to execute a lot of simulations to fully understand the potential of the module. Hence, a decoupling of the hydrodynamic module is made, where the nine different design storms are run as usual hydrodynamic simulations. However, they are saved as three decoupled files. Two of the files include the calculations of flux and area. In addition, the third file is the specification file which is used as the new main modelling file and is consequently the basis for the particle track simulations (DHI 2017b).

Another aspect in relation to the decoupled model is that it is efficient both in terms of time and storage wise, since the particle track simulations can be run without creating new hydrodynamic output files for every simulation run. Due to this feature, it is only the considerably smaller particle output files that are created for each run, thus saving many hours of simulation time as well as computer hard drive storage.

As mentioned earlier, the particle tracking approach is a rather new concept for the purpose of evaluating peak contributing areas which can lead to the simulations of the particle tracks being required to run several times before finding the right parameters to obtain a result. Consequently, the decoupled model increases the capabilities of the particle tracking module since it enables an enhancement of the simulation frequency.

4.3 Particle tracking module

The particle tracking module is mainly used to simulate how pollutants are transported at sea and in watercourses. However, considering that the intended rain amount of the design storm is at such a high rate, the water level is hypothetically adequate to be able to transport the particles within the catchment. However, this only applies when the decay, settling and flocculation for the particles are set to zero. Although, these parameters are not included within this study since they are primarily used to resemble pollutants with varied properties.

4.3.1 Classes

Depending on the characteristics of the released particles, some of their attributes such as minimum particle mass, maximum particle age and unit are implemented in the classes tab (DHI 2017c).
There is also a possibility to divide different particles that have individual characteristics into separate classes, hence, making it easier to include other variants of tracers if necessary.

By defining the minimum weight and maximum age of the particles, one can avoid particles that, if the decay mode is included, degrade to an insignificant amount. Furthermore, to have a maximum age of particles, the model can get rid of particles that come to a halt in places such as sinks or other low points (DHI 2017c).

4.3.2 Sources

A requirement that must be fulfilled, before it is possible to track the particles, is to implement the source of where the particles are placed within the model. Depending on the purpose of the project, it can be decided if the particles are released as point or area sources. Thus, the point source is a specified position in the model which can be determined, and the area source is defined as a spatial domain where the particles are placed (DHI 2017c). An alternative when modelling the sources is to use either a stationary or moving source. However, this is conditioned by what the purpose of the project is and what is desired to be modelled.

During the modelling, which is a big part of what this project revolves around, a point source approach has been used where particles were placed at specific locations in the catchment which was relevant from a research question point of view. Since most of the water is traveling at its highest speed along the drainage paths, the particles are placed at points within the paths where there is a significant flow, which increases the probability to get the particles moving as well as decreases the risk of the particle getting stuck or infiltrated through the soil.

4.4 Outputs

4.4.1 Hydrodynamic module

When using the MIKE software, there is a wide selection of different outputs to choose from depending on the aim of the study and which module is used. For instance, the hydrodynamic module includes output options such as level of inundation, mass budget, discharge through a cross-section and 2D-flow (DHI 2017b).

For the 2D-flow output, three different formats can be specified: point series, line series and area series. Furthermore, these formats decide whether the results of the simulations are collected as geographically defined points, lines or areas. Since the whole domain of the catchment is of interest within this project, the area series is implemented as an output format. Moreover, when using the area series approach, a polygon is created where the coordinates of the outer perimeter of the polygon are set so that it covers the complete investigated area.

In addition, within the area series, there are still more settings to decide since it needs to be distinguished what level of inundation should be included in the output. Hence, three options are provided which determines the flood and dry parameters of the output. These are the whole area, only wet area and only real wet area (DHI 2017b). The whole area setting intuitively covers the entire area regardless of the wetness of the surface. Moreover, the only wet area deletes land points where the drying depth is higher than the water depth which is similar to the only real wet area setting, however, the difference is that the latter deletes land points where the drying depth is higher than the wetting depth. The drying and wetting depths are, as earlier mentioned, decided in the flood and dry settings in the hydrodynamic module (DHI 2017b).

Mass budget and discharge through a cross-section have, earlier in this section, been addressed and are also selectable outputs. When including the mass budget as an output, it provides calculations and quantifications of evaluation parameters such as the proportion of wet area, real wet area and dry area with regards to the polygon which covers the catchment area (DHI 2017b). Furthermore, it is possible to extract the accumulated volume, energy or mass of the element which are added or removed by the source. The discharge output, on the other hand, offers more limited options since it mainly is focused on the water discharge through a decided cross-section. However, there are a few additional features which can extend the number of output options, which are as follows: positive discharge, accumulated positive discharge, negative discharge and accumulated negative discharge (DHI 2017b).

4.4.2 Particle tracking module

What has been mentioned so far in this section refers to the outputs regarding the hydrodynamic module. Concerning the output of the particle tracking module there are some differences compared to the hydrodynamic one. Although the calculations of the particle tracks are based on the raw data of the hydrodynamic calculations, there is a separate output file which is used to visualize the movement of the released particles as a layer to the hydrodynamic output. Unlike the hydrodynamic output, which are received as dfsu or dfs2-files, the resulting particle tracks are provided as xml-files, thus, keeping the size of the files relatively small in relation to how much data is stored (DHI 2017c).

4.5 Simulation approach

One of the main objectives of this project is to evaluate how a catchment area´s peak contributing area is affected by changing the characteristics of the Chicago Design Storm, regarding duration of the rain event and time to peak. To be able to analyse the effects of the different variants of the CDS, nine separate combinations of the duration and time to peak is implemented in the simulations and can be seen in table 2

Table 2: Combinations of durations and r-values of the different design storms

Duration/r-value	0,1r	0,4r	0,8r
2h	2h & 0,1r	2h & 0,4r	2h & 0,8r
4h	4h & 0,1r	4h & 0,4r	4h & 0,8r
6h	6h & 0,1r	6h & 0,4r	6h & 0,8r

These combinations are then run with the particle sources that are used to track where, and how fast, the water travels within the catchment as well as to distinguish if there are any differences depending on what combination is used.

The design storms last a maximum of six hours, however, the length of the whole simulations is longer since it takes additional time for the water to reach the outlet depending on where in the catchment it comes from. Due to this, the total simulation time is extended to 15 hours.

4.5.1 Particle placement approach

One of the more significant challenges with this study is the particle placement approach, which is used with the purpose of tracking and then later evaluating the peak contributing area. To achieve this, a methodical iterative process is implemented with the aim of effectively gathering the information needed for the analysis, and to obtain as reliable results as possible.

Apart from the obvious dilemma on where to place the particles, one must be aware that the data files might become incredibly large and thus the simulations can be very computationally heavy and then require long runtimes. Furthermore, this is depending on several different factors regarding the particle tracking module where the most significant ones are the number of released particles, the number of particle classes and how many sources, where the particles are released, are included. This is difficult to fully know in advance, however, a lower value of each parameter will, intuitively, result in more manageable data files. Although that scenario would be preferable in a time-efficient perspective, it would be a negative aspect regarding the reliability of the results since it would increase the risk of not including all of the relevant outcomes of the simulations.

After including a varying number of classes during several different simulations, it was decided that eight classes with eight different sources are enough to obtain clear results while the data files, at the same time, are manageable.

4.6 Evaluation parameters

To be able to compare the different hyetographs and their possible effect on the peak contributing area, the resulting hydrograph of each rain event is obtained at the point of the outlet of the catchment. The hydrographs provide the information about the severity of the flood and the temporal aspect of when the peak of the flood occurs.

Furthermore, through the particle tracking approach the distance which the particles are traveling from their source is measured, thus, it can then be evaluated which areas are contributing to the flood peak and if the travelled distance changes depending on the design of the hyetographs. If the use of the varied hyetographs would lead to differences regarding the distance and travel time of the particles, this would suggest that there is an effect which may need to be considered when modelling pluvial flooding.

5 Results

Over the course of this project, nine separate simulations have been conducted to evaluate the nine different design storm scenarios. The results obtained from the simulations are then used to answer the research questions. The results are mostly presented as various graphs, which includes a visualization of the rain-runoff relationship, the effect of different r-values and duration of rain events, as well as the results of the peak contributing distance obtained with the use of particle tracking.

5.1 Rainfall-runoff results

5.1.1 CDS-rains with 2-hour duration and variations of the r-value (0.1, 0.4, 0.8)

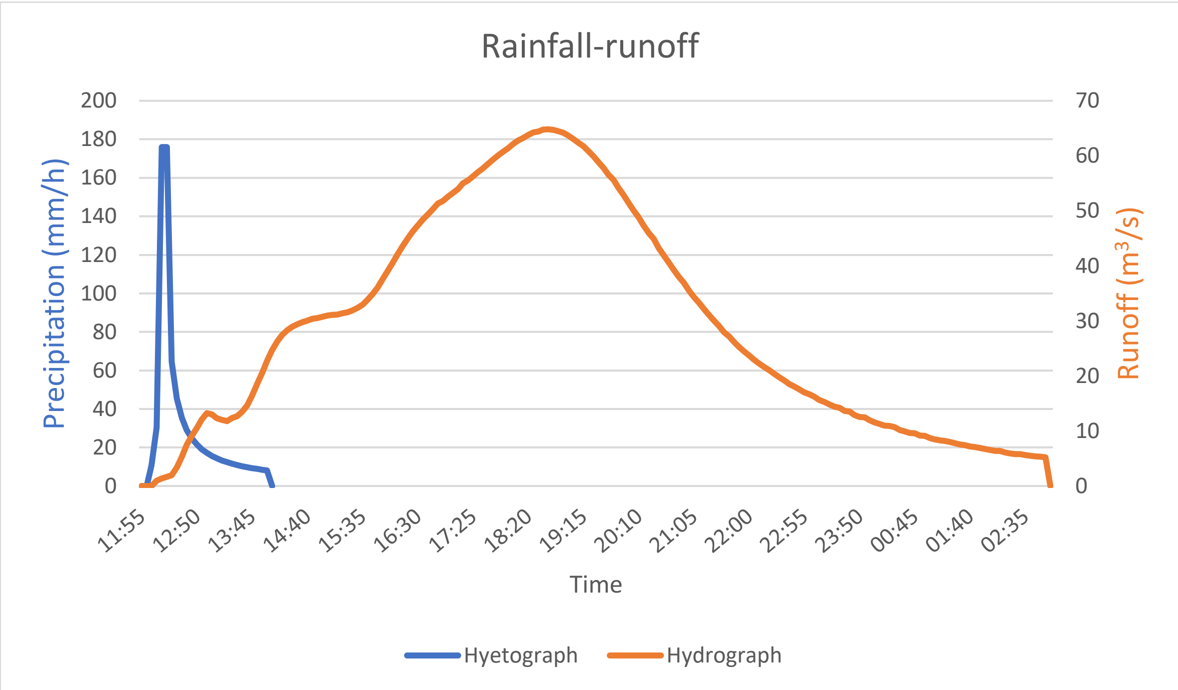

Figure 4: Chicago design storm with a duration of 2 hours and an r-value of 0.1 and its generated runoff

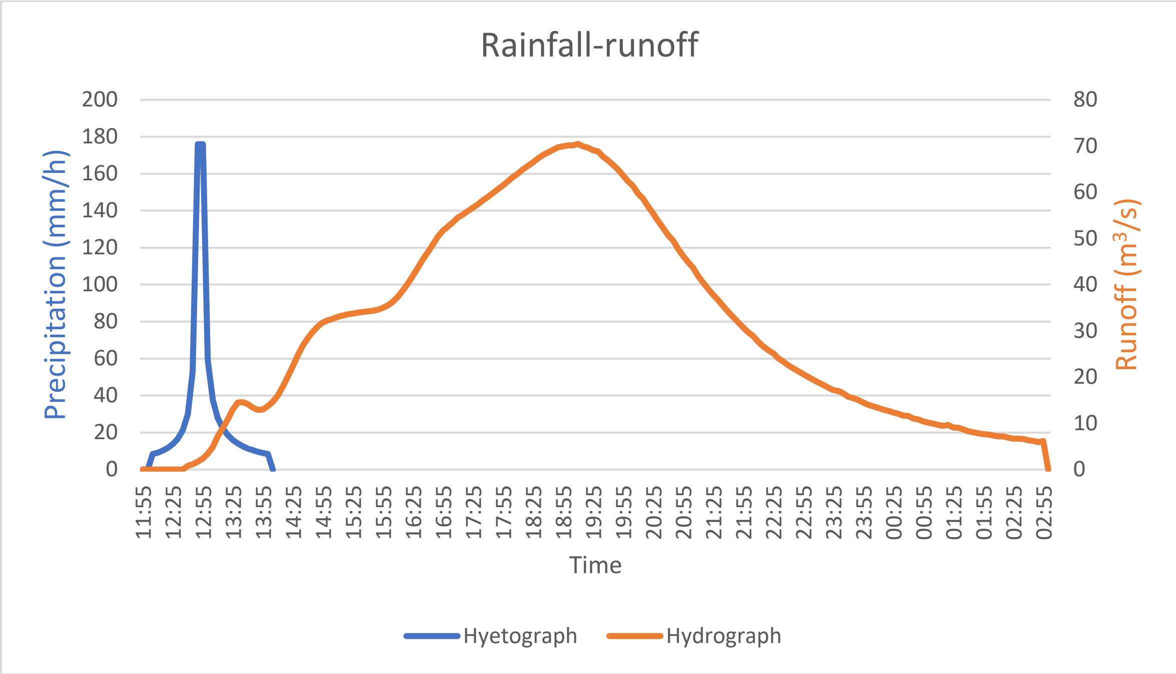

Figure 5: Chicago design storm with a duration of 2 hours and an r-value of 0.4 and its generated runoff

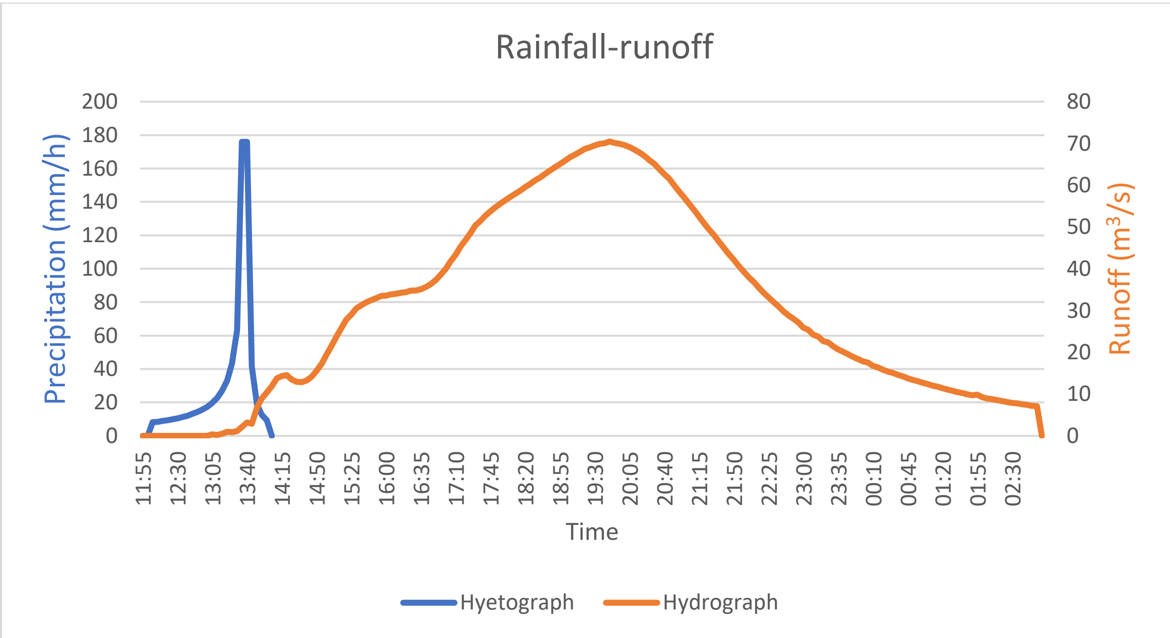

Figure 6: Chicago design storm with a duration of 2 hours and an r-value of 0.8 and its generated runoff

When comparing the different rainfall-runoff events, it is evident that the hydrographs are relatively similar to one another. However, they have a slight difference regarding the discharge rate and the timing of the peak where the hyetograph with the latest peak generates the highest amount of runoff.

5.1.2 CDS-rain with 4-hour duration and variations of the r-value (0.1, 0.4, 0.8)

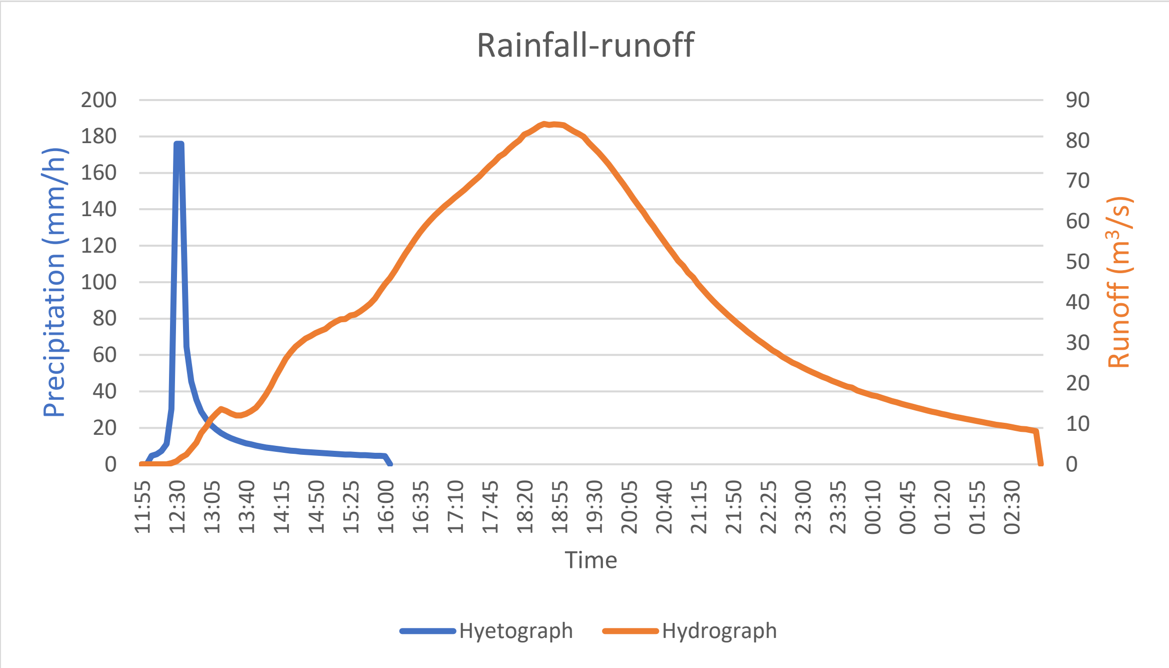

Figure 7: Chicago design storm with a duration of 4 hours and an r-value of 0.1 and its generated runoff

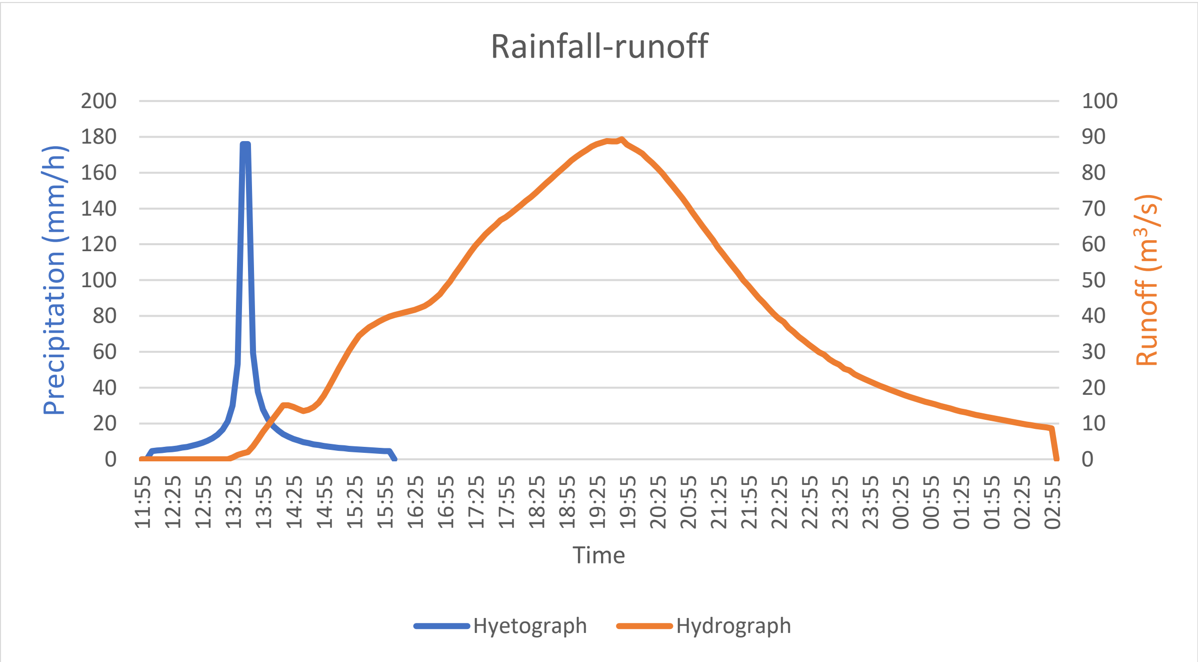

Figure 8: Chicago design storm with a duration of 4 hours and an r-value of 0.4 and its generated runoff

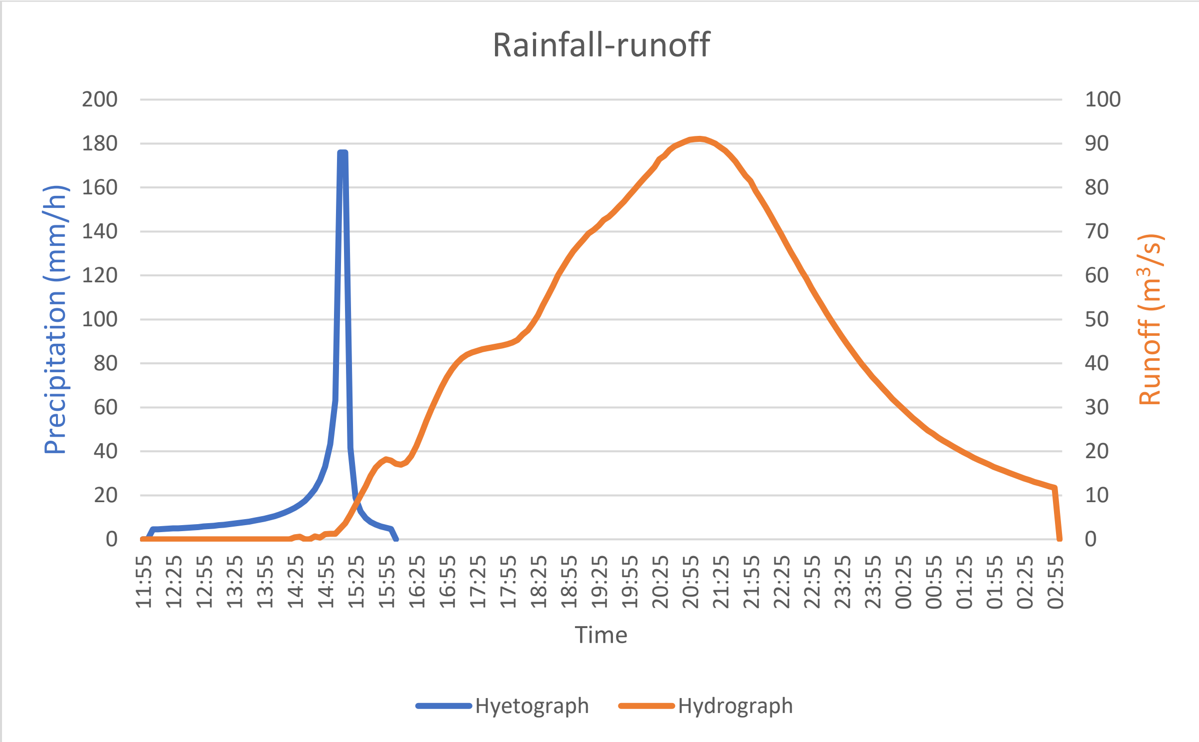

Figure 9: Chicago design storm with a duration of 4 hours and an r-value of 0.8 and its generated runoff

As for the 2-hour rain event, the 4-hour CDS results in a moderately similar shape of the hydrograph when comparing the different r-values. Furthermore, the 4-hour rain follows the same pattern as the 2-hour rain event regarding the discharge and the timing of the runoff peak, where the discharge increases while the peak of the hyetograph is delayed.

5.1.3 CDS-rain with 6-hour duration and variations of the r-value (0.1, 0.4, 0.8)

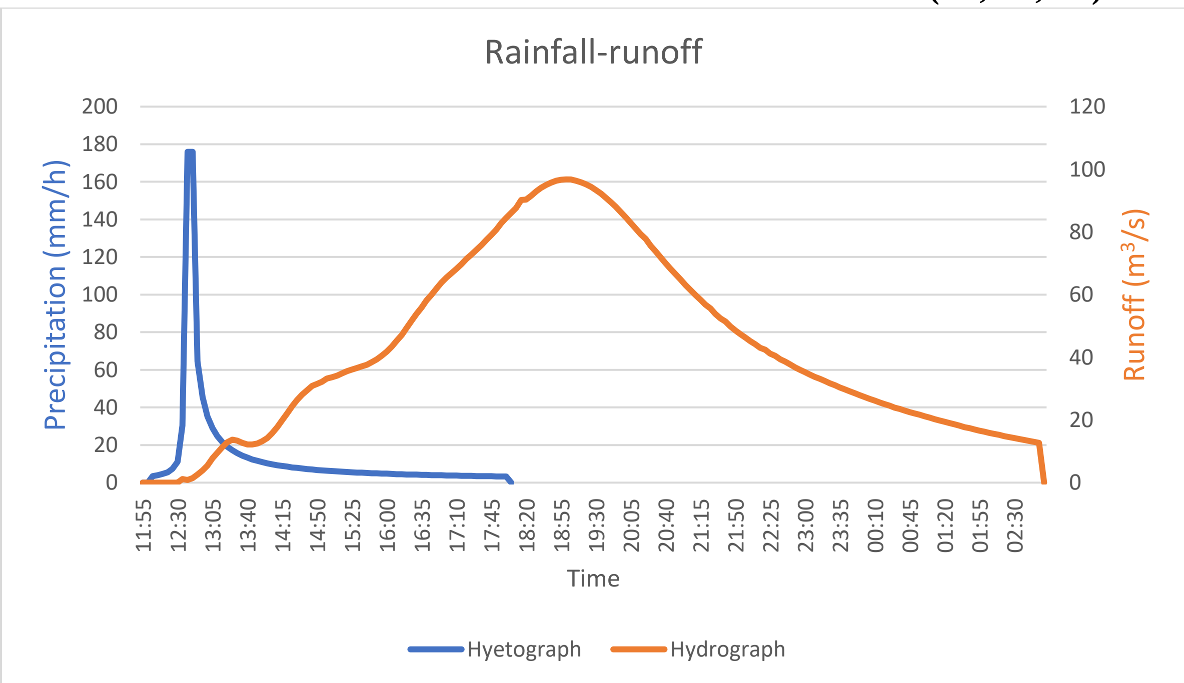

Figure 10: Chicago design storm with a duration of 6 hours and an r-value of 0.1 and its generated runoff

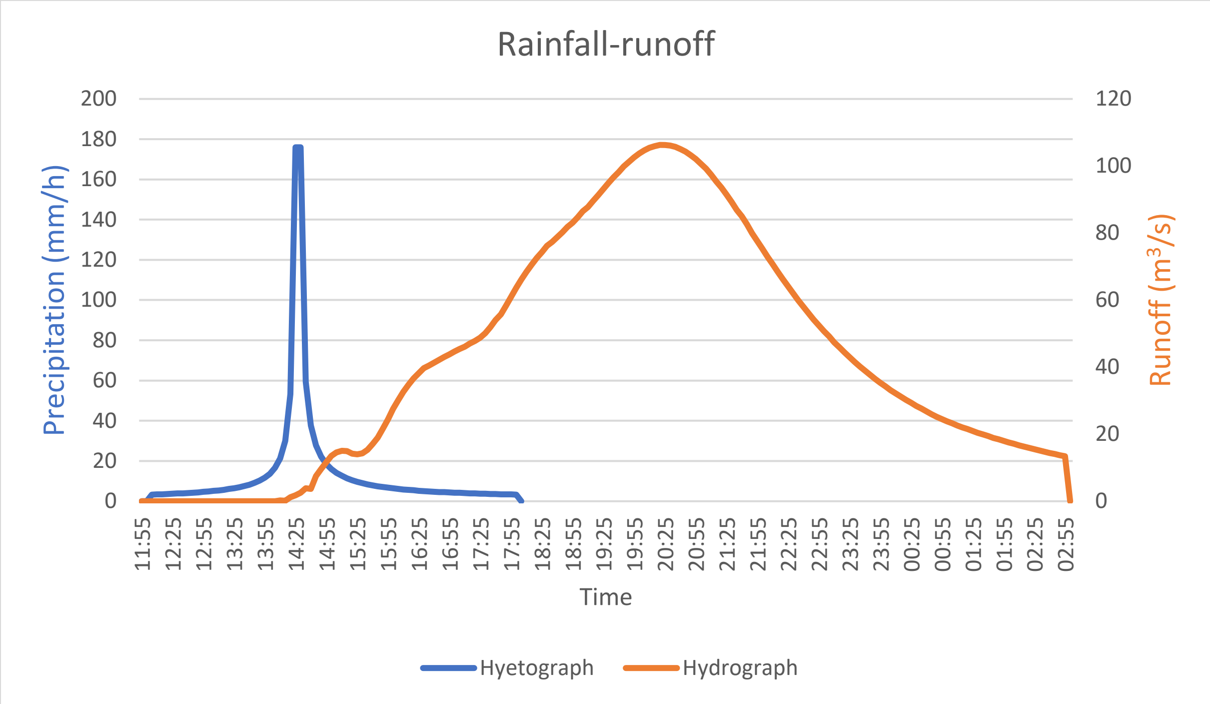

Figure 11: Chicago design storm with a duration of 6 hours and an r-value of 0.4 and its generated runoff

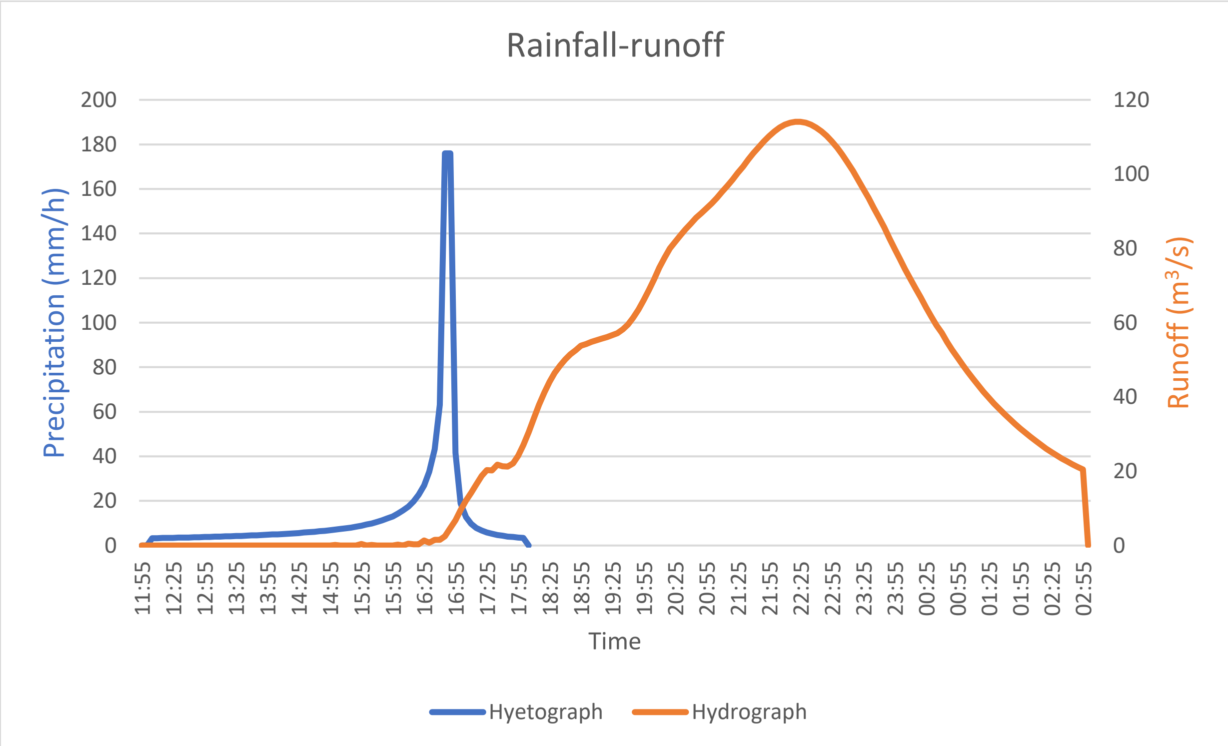

Figure 12: Chicago design storm with a duration of 6 hours and an r-value of 0.8 and its generated runoff

Even the 6-hour rain event follows the same pattern as the earlier two rain durations where the discharge increases in relation to the rising r-value. Also, the shape of the hydrograph does not change significantly depending on what r-value is implemented in the rain simulations.
To make it easier to compare the different results, the main evaluated parameters are shown in table 3.

Table 3: Quantification of the timing of the precipitation peak, lag time between the peaks of the rain and the runoff, maximum discharge, and accumulated discharge until the peak of the hydrograph

CDS-event	**Timing of precipitation peak**	**Lag time (minutes)**	**Maximum discharge (m^3/s)**	**Accumulated discharge until peak (m^3)**
2h-0.1r	12:15	385	64.83	800 470
2h-0.4r	12:50	380	70.46	898 249
2h-0.8r	13:35	370	70.47	875 860
4h-0.1r	12:30	370	84.03	909 172
4h-0.4r	13:35	375	89.33	1 058 230
4h-0.8r	15:10	355	91.08	1 075 170
6h-0.1r	12:40	380	96.78	1 061 790
6h-0.4r	14:25	360	106.26	1 170 250
6h-0.8r	16:25	340	114.09	1 282 590

A specified discharge could be obtained by converting the unit of the discharge from m^3/s to mm/h by dividing the maximum value of the discharge by the area of the catchment and then multiplying it with 1000 and 3600 to convert the units to mm/h. By doing this, it is possible to evaluate how much of the rainfall, per hour, per square meter that reaches the cross-section of the evaluation point of the discharge. The results can be seen in table 4 where it is evident that the amount of rainfall that reaches the evaluation point increases with increasing duration as the area of discharge is the same, the discharge rate in table 4 is proportional to the volumetric flow reported in table 3. Although, the maximum specified discharge of the 0.4r and 0.8r of the 2-hour event are identical.

Table 4: Comparison of the maximum specified discharge generated by the different design storms

Design storm	**Maximum specified discharge (mm/h)**
CDS-2h-0,1r	3.64
CDS-2h-0.4r	3.96
CDS-2h-0.8r	3.96
CDS-4h-0.1r	4.73
CDS-4h-0.4r	5.02
CDS-4h-0.8r	5.12
CDS-6h-0.1r	5.44
CDS-6h-0.4r	5.97
CDS-6h-0.8r	6.42

5.2 Hydraulic response

5.2.1 Difference in time to peak with varying duration

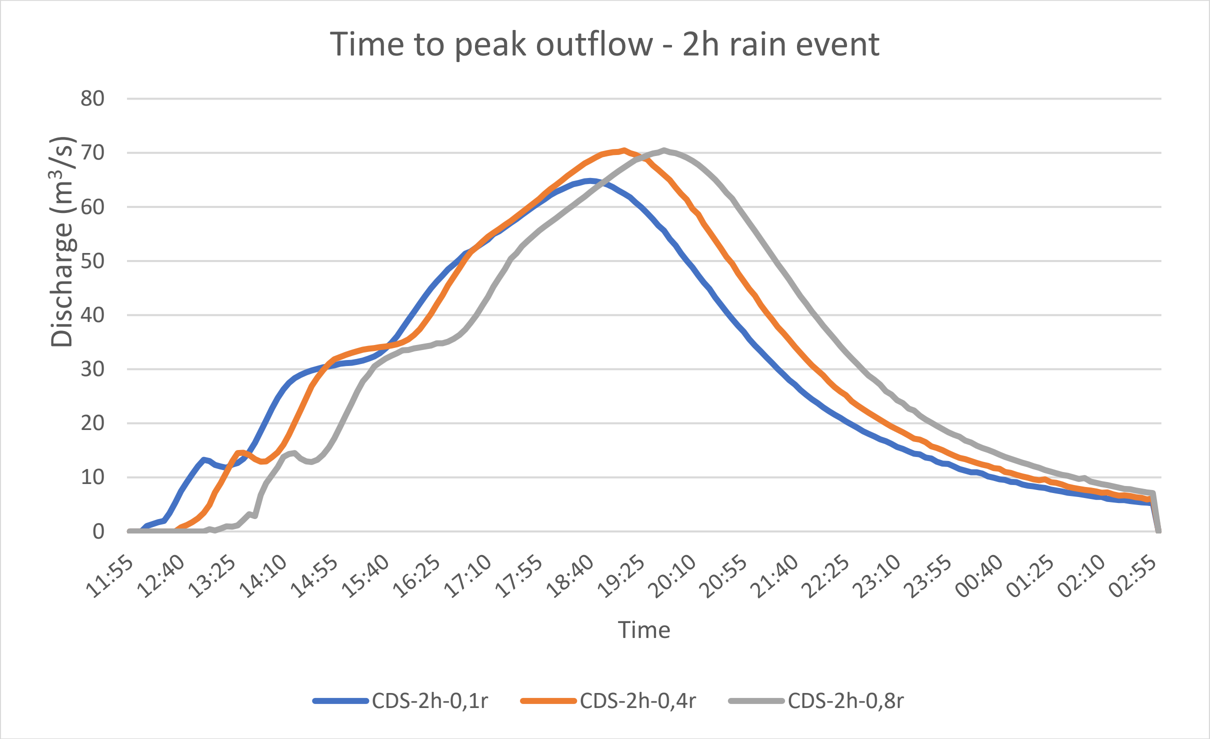

Figure 13: A comparison of the hydrographs of the 2-hour event with varying time to peak of the design storm

The effects of the variation in r-value becomes more noticeable when combining the different hydrographs in the same graph which can be seen in figure 13. For the 2-hour CDS-rain, it is expected that the peaks of the discharge hydrographs are at a relatively similar pattern, regarding the timing of the peak, as between the peaks of the three hyetographs of the rainfall. However, the time difference between the peaks of the hydrographs is slightly less than between the peaks of the hyetographs where the difference between 0.1r and 0.4r are five minutes shorter than between the hyetographs of the same couple. In addition, the time difference for the hydrographs of 0.4r and 0.8r are ten minutes shorter than the difference of the hyetographs of the same r-values.

Moreover, a remarkable aspect that might be of interest is that, while there is a difference regarding the timing of the peak, it is only the discharge rate of the 0.1 r that stands out. The discharge for the 0.4r and 0.8r is somewhat similar while the 0.1r is visibly lower.

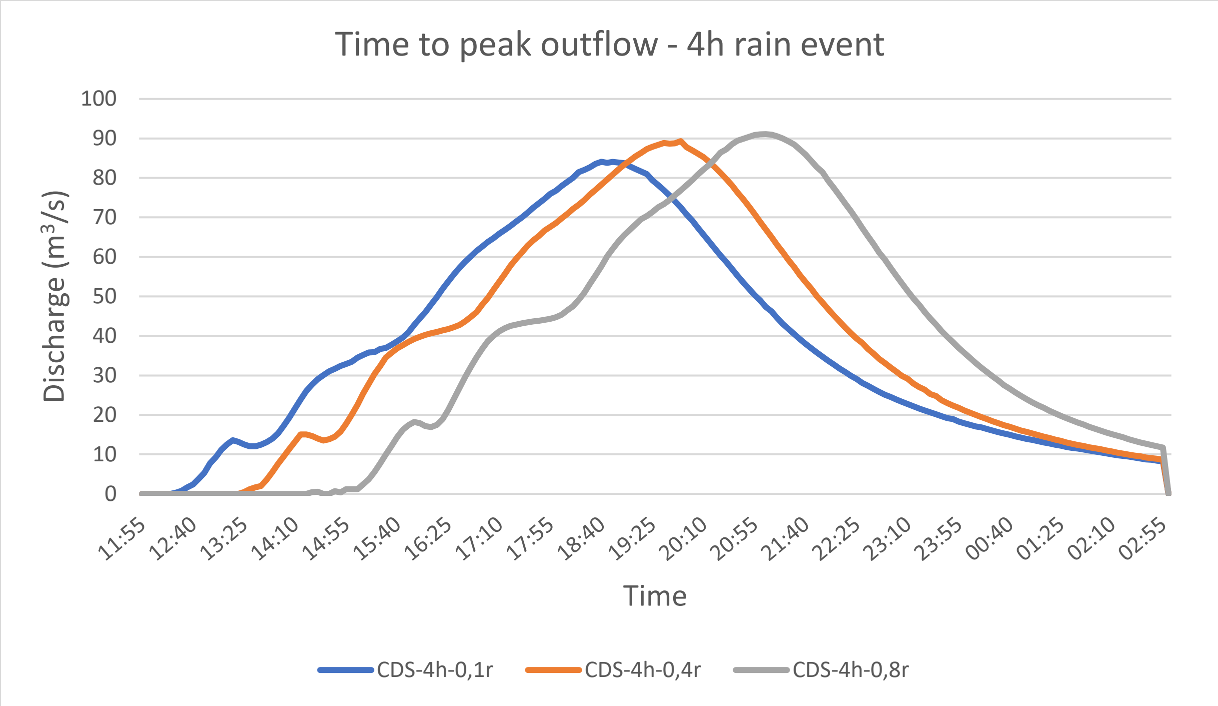

Figure 14: A comparison of the hydrographs of the 4-hour event with varying time to peak of the design storm

It is possible to distinguish certain differences of the hydrographs of the 4-hour rain event compared to the 2-hour event. Firstly, the peaks of the 4-hour event are more temporally separated which can be seen in figure 14. Secondly, the time difference between the hydrographs of the 0.1r and 0.4r is larger than the difference between its hyetographs. However, it is the opposite between the 0.4r and 0.8r where the hydrographs result in a lesser difference than for the hyetographs.

Lastly, all the 4-hour hydrographs generate higher rates of discharge than the 2-hour event. Although, as for the 2-hour cloudbursts, the peak of the 0.1 hydrograph differs more significant from the other two peaks which are much closer with regards to the discharge.

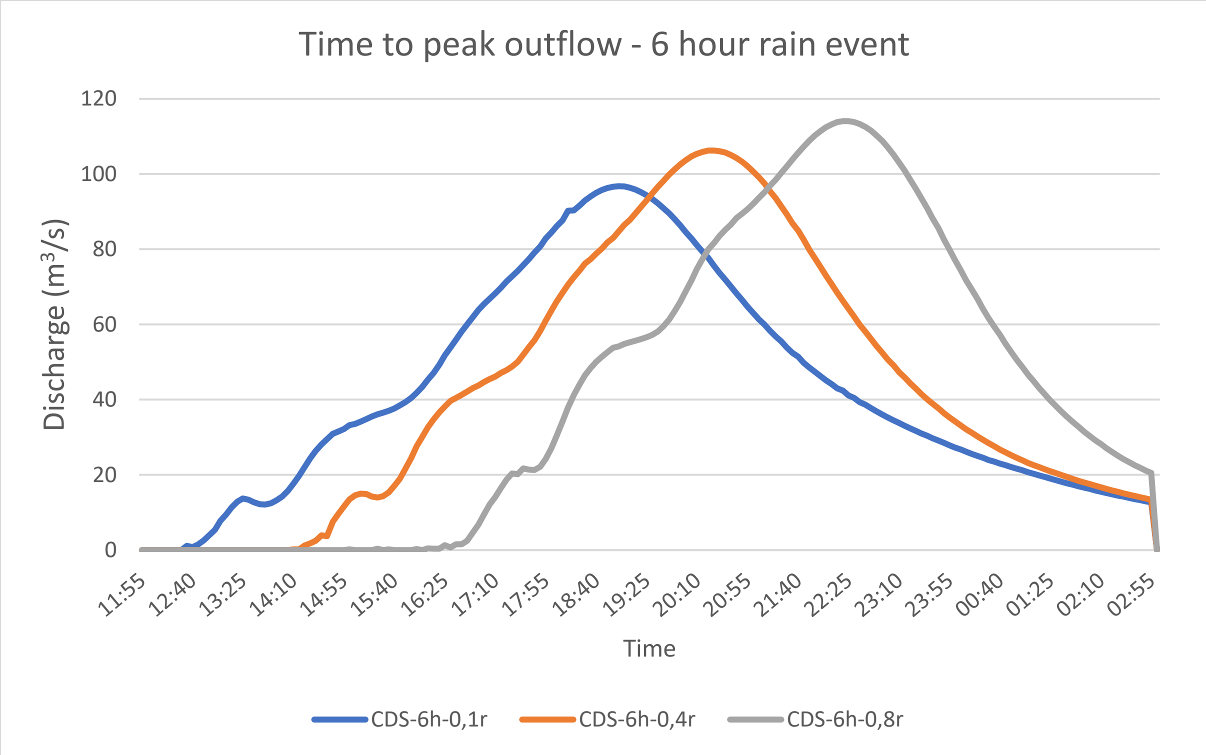

Figure 15: A comparison of the hydrographs of the 6-hour event with varying time to peak of the design storm

The different variants of the 6-hour rain event causes more distinct hydrographs than the other two rain durations as shown in figure 15. The peaks are clearly separated both in a temporal aspect, but also in a discharge point of view. What stands out the most, unlike the previous two rain durations, is that the 0.4r and 0.8r have a more noticeable difference in discharge rate.

5.2.2 Difference of time to peak with a variation of the r-value

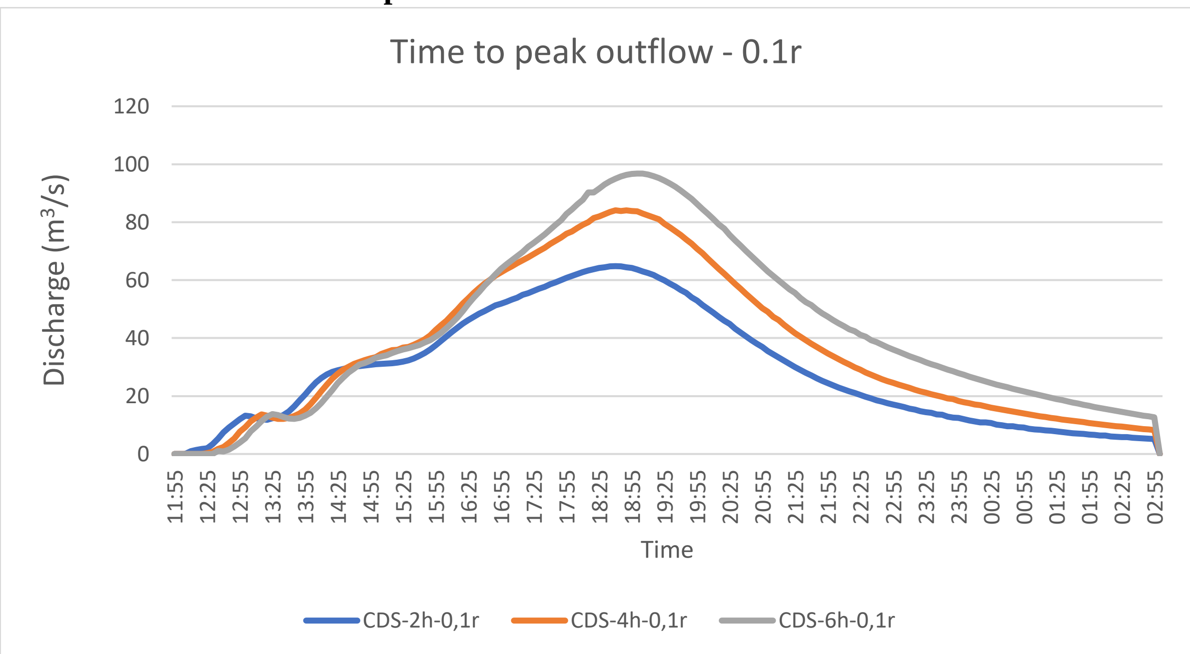

Figure 16: A comparison of the hydrographs generated by the design storms with 0.1 r-value but varying duration

When comparing the different rain durations that have the same r-value of 0.1 in figure 16, it is obvious that the 6-hour event creates the highest amount of runoff. However, the time difference of the peak outflow between the three rains is relatively modest.

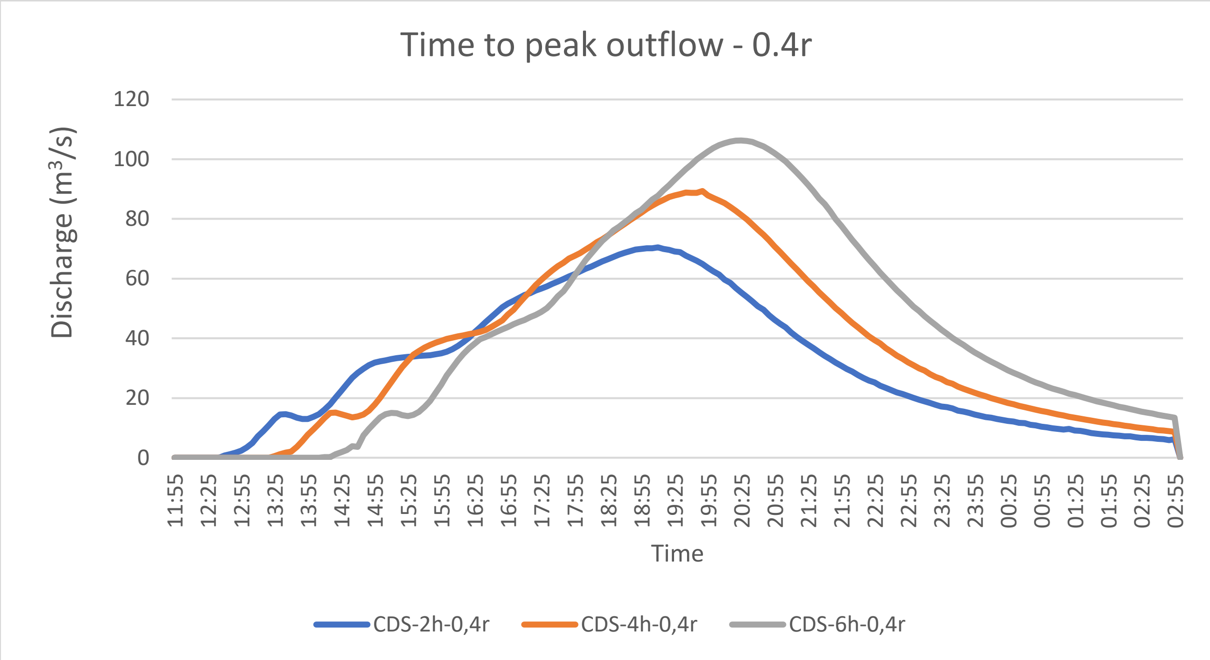

Figure 17: A comparison of the hydrographs generated by the design storms with 0.4 r-value but varying duration

Like the figure showing the r-values of 0.1, figure 17 indicates a similar pattern regarding the discharge rate, although, the time differences between the peaks have increased compared to the rain events with 0.4 r-value.

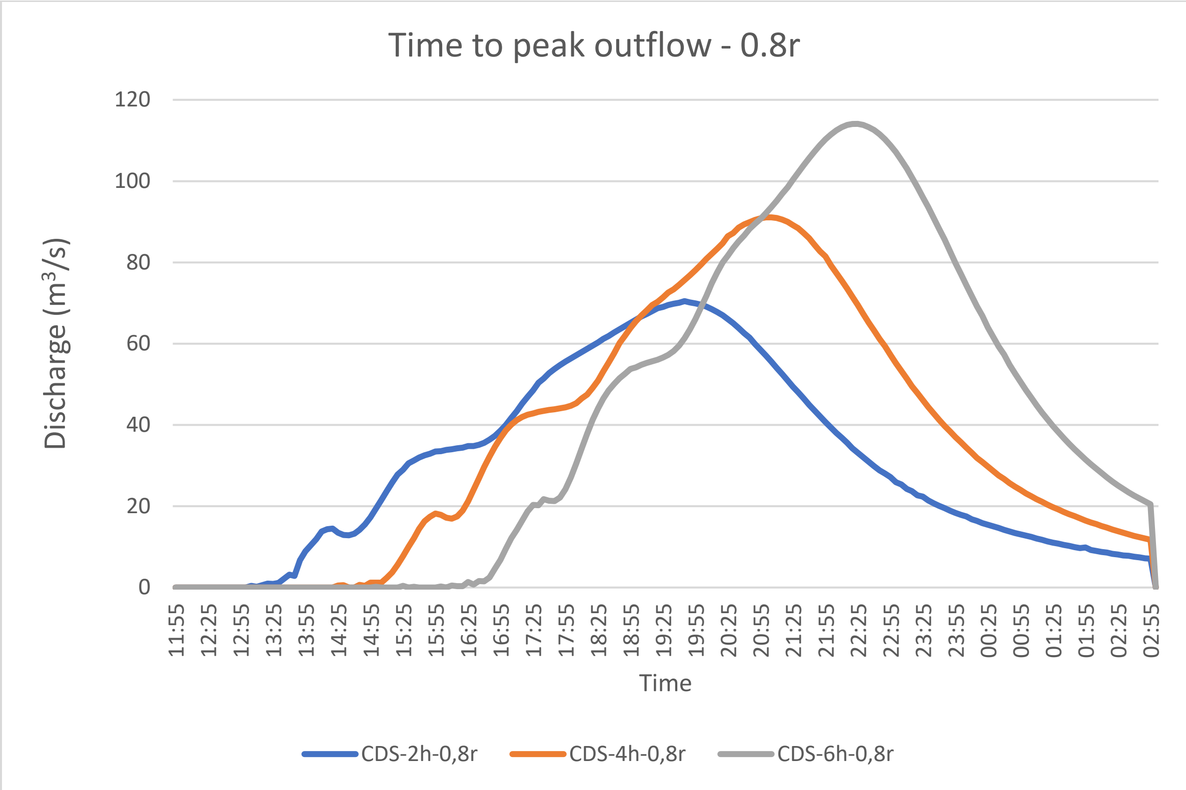

Figure 18: A comparison of the hydrographs generated by the design storms with 0.8 r-value but varying duration

When observing figure 18 in combination with figure 16 and 17, it is evident that the cloudbursts with r-values of 0.8 results in greater variations regarding the discharge at the outlet of the catchment and then, consequently, the hydraulic response. In summary, in comparison of the three durations, the temporal distance of the peaks of the hydrographs is at its largest when the r-value is at 0.8. The percental difference of the generated runoff by the different design storms increases as the duration and the r-values are increased.

5.2.3 Peak contributing distance

The particles that arrived at the outlet of the catchment before the flood peak was reached, are also seen as the ones contributing to the flood peak. Hence, the distance between the location from where these particles were placed and the outlet of the catchment is presented in this section as the peak contributing distance. This was measured for the different durations individually as well as compared jointly.

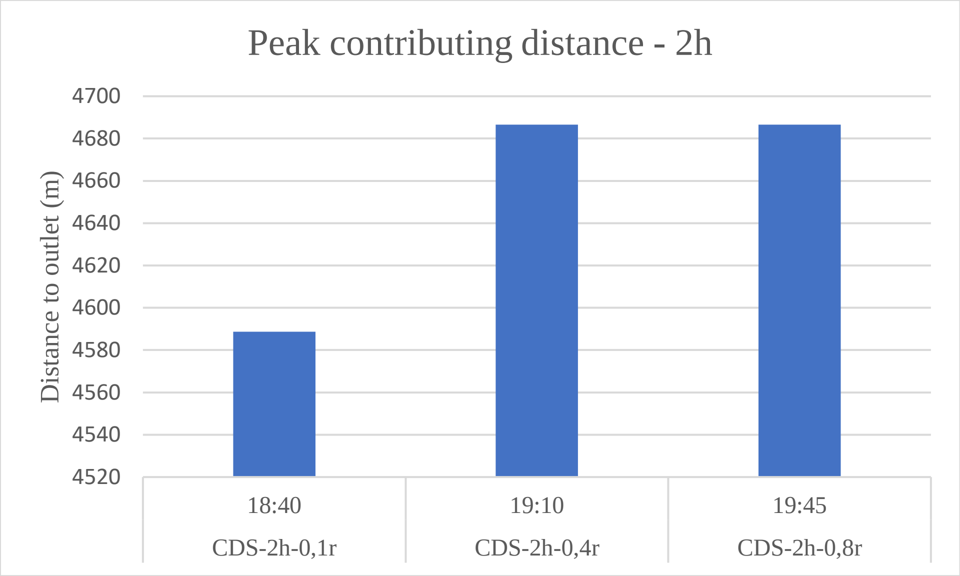

Figure 19: A comparison of the peak contributing distance of the design storms with 2-hour duration and varied r-value. The timing of the hydrograph peak is presented beneath the bars.

The 2h-event displays, in figure 19, a difference in contributing distance between the rains with r-values of 0.1 and 0.4, where the peak contributing distance for the 0.1r-rain is approximately 4589 meters while it is 4686 meters for the 0.4r-rain. Hence, the difference of peak contributing distance is 97 meters. Furthermore, there were no visual difference in the peak contributing distance between the rains with 0.4r and 0.8r since the particles arriving, at the evaluation point, until the flood peak had the same source for both events, even though they reached the evaluation points at different times.

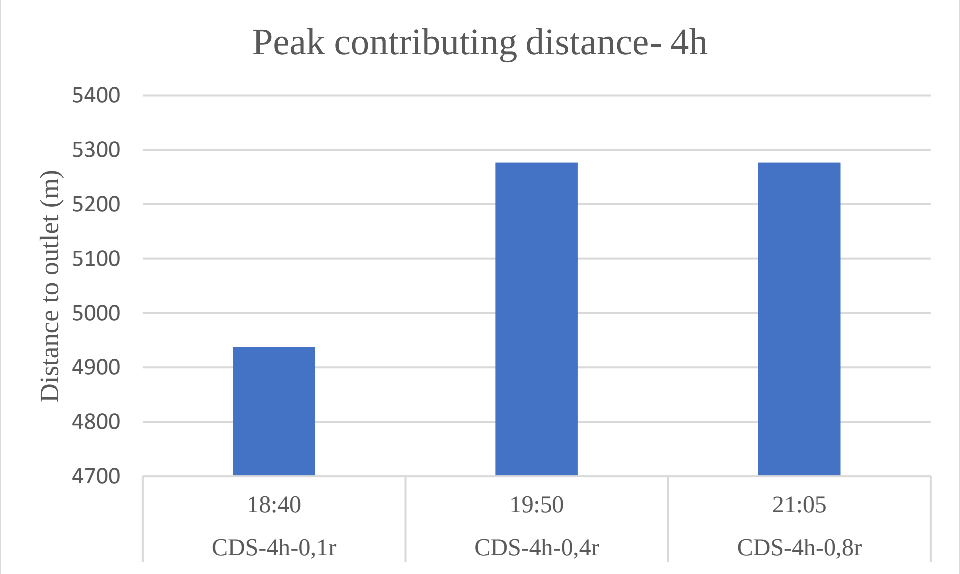

Figure 20: A comparison of the peak contributing distance of the design storms with 4-hour duration and varied r-value. The timing of the hydrograph peak is presented beneath the bars.

The same pattern is noticeable for the 4h CDS-event in figure 20 as for figure 19, where the CDS-event with 0.1r results in a significantly shorter peak contributing distance than the CDS-events with 0.4r and 0.8r. Consequently, the 0.1r-rain resulted in a peak contributing distance of 4938 meters compared to 5278 meters of the 0.4r and 0.8r.
In addition, as for the 2h-event, the 4h-event shows similar results for the CDS with 0.4r and 0.8r where the peak contributing distances are indistinguishable from one another.

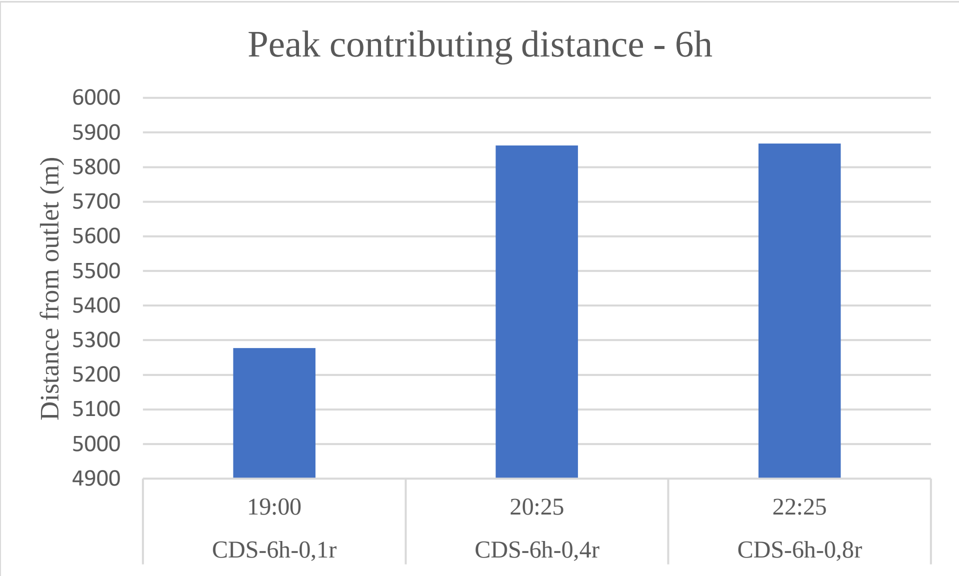

Figure 21: A comparison of the peak contributing distance of the design storms with 6-hour duration and varied r-value. The timing of the hydrograph peak is presented beneath the bars.

As the duration increases, so does the general peak contributing distance, as well as the distance difference between the 0.1r and 0.4r of the 6h CDS-events. For the 0.1r-CDS, the peak contributing distance reaches up to 5277 meters from the outlet. For both the 2h-event and the 4h-event, there were no noticeable range differences between the 0.4r-rain and the 0.8r-rain, which has been presented in figure 19 and 20. However, it was manageable to detect a slight dissimilarity in peak contributing distance for the 0.4r and 0.8r of the 6h-CDS, where the 0.4r resulted in a peak contributing distance of 5862 meters whereas it was 5868 meters for the 0.8r. Although, since there are some uncertainties within the model, one can assume that it is similar for the two rain events.

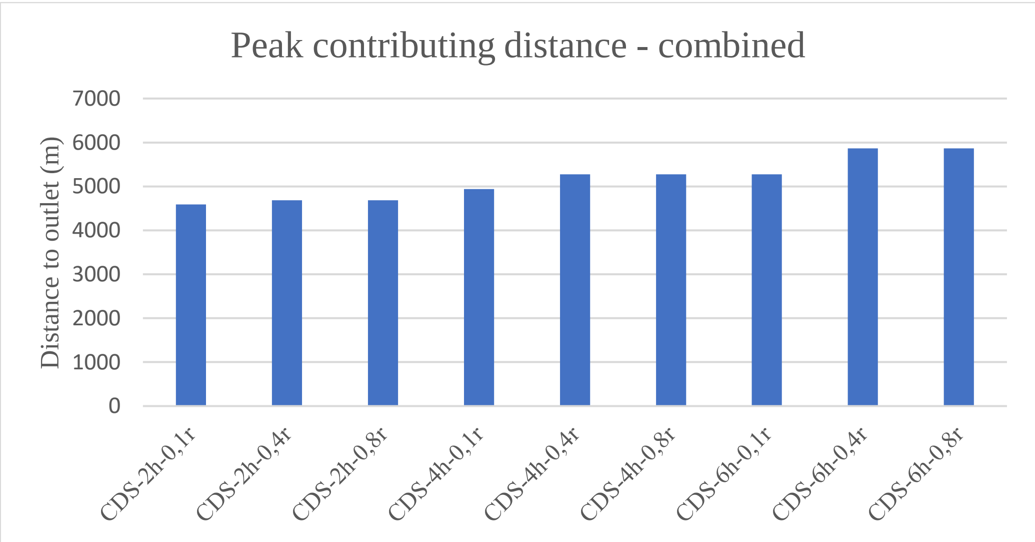

Figure 22: All of the different peak contributing distances combined

When combining all the different peak contributing distances for the various rain events in figure 22, it is evident that the peak contributing distance increases when the duration is extended. The maximum difference in distance occurred between the CDS-2h-0.1r and CDS-6h-0.8r, which differed 1279 meters. Moreover, the rain event that resulted in the greatest difference within the same duration was the 6h-CDS, where the peak contributing distance differed 591 meters. The distance that the particles travels for each design storm is visualized in figure 23.

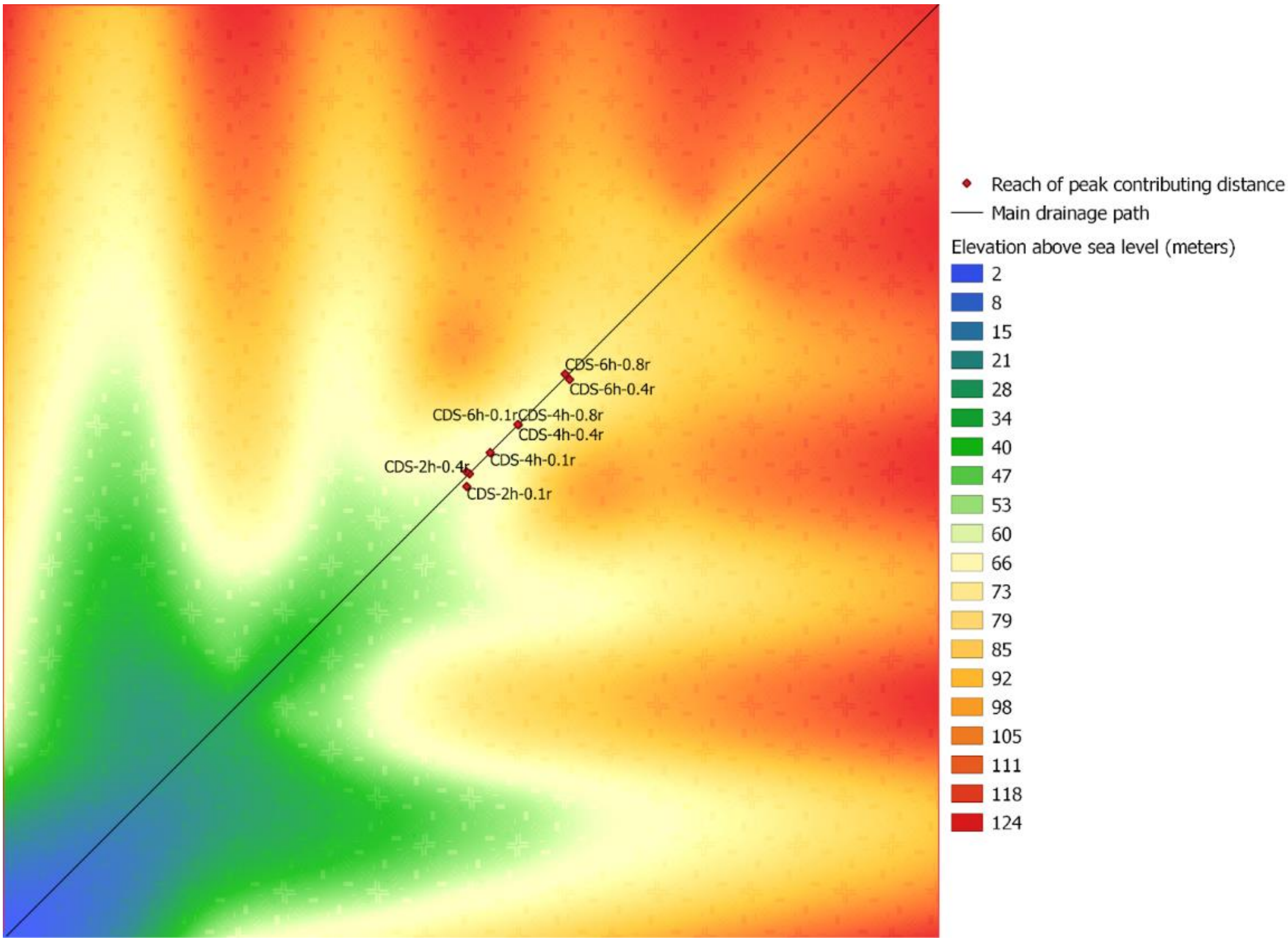

Figure 23: The different peak contributing distances visualized as points along the main drainage path

6 Discussion

One of the main aims of this study has been to extend the knowledge of how peak contributing areas are affected by different duration, in combination of variation of the time to peak of the hyetographs, of the Chicago Design Storm. Elfström & Stefansson (2021) determined that the peak contributing area grew with increasing duration. However, they also concluded that when the peak contributing area were geographically larger than the rain event, it could no longer be measured. Hence, a uniform rain event, located over the whole catchment area, was used in this study. The reason for this was so that the effects of which the duration and time to peak of the rain could have on the peak contributing area would be thoroughly examined.

To be able to follow the water´s flow path and travel times from specific areas inside the catchment, a particle tracking approach was chosen with the hypothesis that by following the particles from the placement point to an evaluation point by the outlet, one could estimate the size of the peak contributing area. This was done with the assumption that all the particles that reached the outlet of the catchment before the flood peak then contributed to the peak. This could then be translated to involving the areas of the particle´s origin, thus, the peak contributing areas would then be identified.

6.1 Urban catchment

As described in section **4.1.3**, the model is built to contain 400 identical squares where each is 160 000 m^2. These are made to mimic residential areas in the catchment; thus, they include houses, roads and green areas as well as some submerged areas where the water slows down or even comes to a halt. Furthermore, the slope of the catchment is mainly aiming towards the outlet, however, there is a slope that is angled partly along the branches, but also perpendicular to them. This results in that the water travels from the more planar areas towards the branches of the catchment which then acts as a watercourse that transports the water towards the outlet. This naturally leads to a higher water flow through the catchment´s branches since the rain falls over an area that contributes water from both sides of the branch. However, there are still residential areas where the watercourses arisen, hence, the water does not have a straight path to the outlet but moves between the houses and over the green areas as well as the roads. Consequently, the flow of the water is decreased compared to if it would be a proper channel with no obstacles.

Since the scope of the study mainly focuses on the hydraulic effect of the variations of the design storms, there were not any changes to the input parameters of the catchment.

In order to avoid that the catchment´s input parameters affect the hydraulic response in any extreme direction, the mean value of the parameter spectrum is used. Furthermore, the hydrodynamic model is meant to characterize pluvial flooding in an urban area where the capacity of the sewer system has been reached, as well as there are no, already existing, waterways since that also would include fluvial flooding which is beyond the scope of this thesis.

6.2 Particle tracking module

The main purpose of the particle tracking module is to follow and visualize the motion of pollutants in watercourses such as rivers, lakes and seas. However, it can also be used to track the flow of water since the particle's trajectory is calculated from the hydrodynamic calculations of the movement of water. The hypothesis in the beginning of the project was that if the characteristic of a particle is similar to the properties of a water drop, it could suit as a tracer for the catchment area. Moreover, with the use of this tracer, the peak contributing area was to be identified and analysed how it is affected by the variability of the duration and time to peak of the design storm.

The challenge with using synthetic particles when modelling a synthetic catchment area is to assure that the particles are moving in a realistic manner. To do this, one must make estimates based on the travel time for the particles in relation to the velocity of the water flow, as well as to assess whether the paths of the particles are reasonable. However, since the particle tracking module uses instant acceleration within the hydrodynamic calculations, the particles move at the same speed and direction as the water in the same grid cell as the particle. This implies that there is no settling, decay nor dispersion of the particles. On the other hand, this indicates an uncertainty as the grid cells of the model is 10x10 meters and could impose a weakness as a model with smaller grid cells most likely would be more precise in terms of resolution. Although, with larger number of grid cells, the model´s efficiency regarding the simulation time increases. This was taken into consideration, but given the size of the model area, the decision was made that the simulation time would be too extensive by decreasing the size of the grid cells. However, it should be mentioned that a grid convergence analysis has not been done for this thesis.

6.2.1 Particle placement

The work of developing a method for, not only identifying, but also analysing contributing areas was initiated by placing particles uniformly across the catchment at approximately 1000 meters apart, which was supposed to give an overview of how the particles moved within the model area. However, it was relatively soon apparent that particles placed outside of the channels had difficulties moving even tens of meters. The reason for this is suspected to be due to the fact that the flood depth, as well as the velocity of the water, outside of the channels were too low for the particles to drop from their initial positions. This, of course, affected the original research questions which included the examination of the peak contributing area since a much smaller area of the catchment could be included.

Instead, the focus turned towards placing the particles within the drainage paths of the catchment which naturally transport a larger amount of water and therefore increased the probability of the particles to follow the stream of water. The purpose of this was to obtain a peak contributing distance which then could be an indicator of how the peak contributing area would be affected under similar circumstances. This mode of procedure seemed to work initially, although, after completing a couple of simulations it was evident that the particles also had trouble moving through the branches of the drainage paths which would reduce the reliability of the results. However, the particles could move relatively well throughout the main drainage path which lead to the decision to only focus on the central line of the catchment area regarding the placement of the particles.

To obtain a perception of how far, from the outlet, the peak contributing area reaches, the particles are placed as evenly as possible along the main drainage path. Henceforth, the distance between the placed particles decreased for every simulation run until the distance between the nearest placed particle, to the outlet, and the furthest placed particle was approximately 1700 meters. The reason behind this is that, from what the simulation result says, it is from these positions that the contributing distance varies depending on the duration of the design storms. By having placed particles amidst these two positions, it was possible to evaluate how the contributing distance fluctuated due to the changes of rain duration and time to peak. For the rain events with an r-value of 0.1, the results of which particles reached the evaluation point before the hydrograph peak were relatively easy to distinguish. However, it was more difficult to discern a difference for the design storms with r-values of 0.4 and 0.8, which led to the decision to place the particles more densely at the areas there where ambiguities regarding the differences in the peak contributing distance. Despite the measures, a difference of the peak contributing distance of the CDS with 0.4r and 0.8r of the separate 2h and 4h duration, could not be distinguished. On the contrary, it was possible to determine a slight difference at the evaluation point, of where the particles originated, between the 0.4r and 0.8r of the 6h rain event. Nevertheless, one aspect that needs to be considered is the uncertainty of that when there is a short distance between the sources of the particles, there is a risk that a particle that has been released slightly further up may arrive before a particle released below, which may depend on the flow path of the particle.

6.3 Hydraulic response of the different design storms

In order for the whole catchment to receive an equal amount of rain, a spatial uniform rain was chosen, which provided the opportunity to determine which parts of the catchment area that contributed to the flood peak. The use of the CDS generated results that could rather easily be compared with each other as the CDS, essentially, has similar type of shape regardless of the duration. Although, the shapes of the hyetographs are similar to each other, they produce a varying amount of runoff. Which, for example, can be seen in figures 13 to 18 in the results section. What can also be determined when examining these figures, is that the peak discharge increases when the duration of the design storm is extended. This can partly be explained by the fact that the accumulated amount of rain is greater with increasing rain duration. However, the design storms generate the same amount of accumulated rainfall regardless of the time to peak of the rainfall, which can be seen in figures A1 to A3 in appendix A. Furthermore, it is also evident that the results indicates that CDS-events with r-values of 0.8 results in a larger amount of discharge than design storms with r-values of 0.1 or 0.4, which also follows the pattern of previous research such as by Qin et al. (2013).
This is seemingly due to the infiltration capacity changes during the rain event as the soil of the catchment does not reach the same degree of saturation when using a CDS with 0.1r than with 0.8r. Hence, from what it seems, a larger proportion of the 0.1r design storm peak is infiltrated, while for the CDS with 0.8r the soil is already saturated before the rainfall is at the peak of its intensity.

When comparing figures 13, 14 and 15 in the results section, one aspect which is not obvious is that for CDS-events the 2h and 4h durations have a similar pattern regarding the produced discharge by the rainfall events with 0.4r and 0.8r. The percental difference of the discharge, which was presented in table 4, between the r-values of 0.4 and 0.8 for the 2h event was only 0.013%, while it was slightly larger, 1.93%, for the 4h duration. Furthermore, this can be compared to the percental difference of peak discharge that separates the 0.1r- and 0.4r-events, where the 0.4r produced 8% more than the 0.1r for the 2h-event. Moreover, the difference of the peak of the produced discharge between the 0.1r and 0.4r for the 4h-rain event was 5.85% in the 0.4r-event´s favour. However, the 6-hour event resulted in much less differences, although, the percentage difference of the produced discharge was still closer between the 0.4r and 0.8r than between 0.1r and 0.4r.

From a hydrologic perspective, these results should support the earlier statement that CDS-events with a centred or late peak rain intensity tends to saturate the soil more, and consequently produce higher amounts of runoff than CDS-events where the temporal position of the peak rainfall intensity is early.

6.4 Peak contributing distance

As mentioned earlier in the discussion, there were some issues with the particle tracking where the particles placed outside of the main drainage path had difficulties to reach the outlet of the catchment, thus, the evaluation of one of the original aims, i.e., how variations of the Chicago Design Storm affect the peak contributing area of an urban catchment had to be changed. Following this, the focus shifted from the area perspective towards a peak contributing distance approach, which was concentrated to the main drainage path, hence, it transports the largest amount of water and may be an indication of the response of the catchment in whole. In addition, since the modelled catchment in this study was relatively large, it is possible to connect the results to the study of Beven & Kirkby (1979) who claimed that, for larger catchments, the areas contributing to floods were more concentrated to the vicinity of the channels of the catchment areas compared to small-scale catchments where the contribution was more widespread. This is also aligned with the study conducted by Buchanan et al. (2012), where the areas contributing to flood were adjacent to the stream network and then spread out to other parts of the catchment. The tendency that the contributing area is concentrated along the stream network was also seen when monitoring the results of this study.

With the use of the particle tracking, it was possible to obtain a quantitative figure of how far up in the main drainage path of the catchment area that the rainfall contributes to the peak outflow. Furthermore, due to the use of particles as a tracer element, the travel path of the water becomes a factor that can influence the travel times of water, which otherwise would have been difficult to examine.

After conducting hydrodynamic simulations, as well as particle track simulations, for the decided design storms, the results shown in figures 19 to 23 could be obtained. These results indicates that different rains have a varying impact on the peak contributing distance. For instance, the rainfall from the 6-hour CDS, with 0.8 r-value, that contributed to the flood peak fell approximately 1279 m further up in the catchment than the 2-hour, with 0.1 r-value, CDS. These were the ones that differed the most, however, in a separate comparison of the different durations a pattern is distinguishable where the design storm with r-values of 0.1 resulted in a shorter peak contributing distances than the rain events with the same duration but with r-values of 0.4 and 0.8. Although, one very interesting aspect is that every examined duration resulted in a noticeable difference of the peak contributing distance between the rains with r-values of 0.1 and 0.4, albeit there was only a scarce distinction amongst the design storms with r-values of 0.4 and 0.8. This indicates that the timing of the peak of the rainfall is more relevant, regarding peak contributing distance, whether the peak is early or centred, rather than if it is centred or late. The reason behind this can presumably be related to the percental differences of runoff of which the variation in time to peak of the design storms causes. In addition, this was mentioned earlier in the hydraulic response section of the discussion, although it was not further elaborated regarding the underlying cause of this.
The most plausible explanation is that the infiltration capacity reaches a threshold value that is in the vicinity of when the design storms r-value is 0.4. Thus, when the threshold value is reached, the timing of the peak of the rainfall ceases to matter.

However, for future research, it would be interesting to assess how the peak contributing distance, or area, behaved if empirical rain events were implemented in a hydrodynamic model. In addition, one can assume that the peak contribution, also, would differ if using a spatially varied rain when modelling. Although, Elfström & Stefansson (2021) already have touched upon that subject and discussed the risk of that the peak contributing area is larger than the spatially varied rain and therefore cannot be fully analysed.

6.5 Method review

The use of a particle tracking approach has been a very interesting way of evaluating how the different design storms affect the hydraulic response, within a catchment area and not only by the outlet. However, the project has encountered some problems along the way, which have required some compromises and consequently resulted in minor changes of the original objective.
One of the initial aims of the study was focused on how peak contributing areas was affected by using different variants of the duration and time to peak of the Chicago Design Storm. To achieve the aforementioned aim, one of the requirements was to be able to freely place the particle over the catchment and that the placed particles then would reach the evaluation point. The particle tracking module easily allows the particles to be placed wherever they are desired, however, it was proven to be more difficult than expected for the particles to reach the outlet depending on where they were released. Due to this issue, the research focus shifted towards the central channel which, practically, runs through the entire catchment and therefore might be an indicator of how the total area ought to behave regarding the peak contributing aspect.

Moreover, since the particle tracking approach is an unproven method for this type of objective, there are initially no guidelines to follow to achieve the best possible results. From this perspective, the work has primarily been very iterative, which is time consuming when done manually. The choice of using a decoupling of the hydrodynamic model was crucial to be able to find the right placements of the particles, thus, then the hydrodynamic simulations only needed to be done once for each rain event. In addition, it allowed the particle tracking simulations to use the calculations of the hydrodynamics instead of running both simulations at the same time. Consequently, this saved a lot of time since the time difference between a hydrodynamic simulation and a particle track simulation, based on a decoupled model, could be up to 6 hours.

As mentioned earlier in this section, a part of the method development was iterative, which mainly included the procedure of the particle placement. Furthermore, the idea was to place the particles evenly spaced between each other with a relatively large distance at the beginning, to then reduce the distance for each run until a distinct result could be obtained. This implied that the particles tendency to move from the placement point was the same regardless of where they were placed. However, this turned out to be more complicated than first thought as the mobility of the particles was greatly affected by the type of surface on which they were placed. Accordingly, the particles placed on surfaces that had a potential of generating high flows, such as hardened surfaces with little to none infiltration, increased the probability of the particles moving. Thus, the process was slowed down as each intended particle placement had to be examined, in advance, with respect to the water flow situation at the selected location. Due to this, the distance between the particle placements could thus not be evenly distributed, although, the original purpose of the particles could still be fulfilled. Moreover, there were no automatic way of controlling which particles that reached the outlet, hence, the time-consuming process had to be done manually for every simulation. In addition, the method was not very successful of tracking particles regardless of where in the catchment area they were placed, however, it acted a lot better when the particles were placed in the main drainage path. This implies that there can be a use of the particle tracking approach, although, to achieve the best possible results, the catchment area needs to have a very high water flow, which may not be the reality in every scenario.

6.6 General uncertainties and comments regarding the model

Since the modelled catchment area is completely synthetic and therefore virtual, it is not possible to verify the results by comparing it to a real existing urban catchment validation. However, although the model is virtual, it can still be useful for hydrologic research since it allows the user to freely change the desired parameters of both the catchment as well as the rain event. This provides a broad spectrum of capabilities compared to studies of real catchment which can be more limited. The simulations of tracer particles can also be a supplement of using real tracers as it does not require you to physically dispense a trace element, thus, being more time efficient.

7 Conclusions

The aims of this study were to investigate whether the areas that contributes to peak runoff differ geographically depending on the design storm´s duration and time to peak, as well as if it can be determined by using the travel time of the water from the investigated areas. Furthermore, if the peak contributing area can be used to distinguish what sizes of catchment areas are worth to include when creating models of Swedish urban catchment areas and if it can be depending on the characteristics of the hyetographs. Also, the answer was sought if the particle tracking approach is a reasonable way of evaluating the peak runoff contributing areas, and if the approach has the potential to be a new concept to use when modelling inundation. After evaluating the obtained results and compared how well they answered the research questions, it can be concluded that the study has both been successful, but at the same time encountered setbacks.

Firstly, it was not possible to evaluate the peak contributing areas, but instead the peak contributing distance along the main drainage path. Thus, these results indicated that the varying durations and time to peak of the design storms influence the peak contributing distance. Accordingly, the 2-hour rain with 0.1 r-value led to the least peak contributing distance while the 6-hour rain with an r-value of 0.8 resulted in the longest distance that contributed to the flood peak.

Secondly, the travel times of the water could be used for the evaluation, since it was translated from the travel times of the released particles from the particle tracking approach which were measured by the outlet of the catchment area.

Thirdly, since it was not possible to evaluate the whole catchment area with regards to some of the issues with the particle tracking, it is neither possible to give a convincing answer to what sizes are relevant to include when modelling Swedish urban catchment areas. Although, it is feasible to make broader assumptions.

Lastly, the particle tracking concept was very interesting to work with regarding these research questions. However, the approach was relatively complicated to implement with the chosen circumstances regarding the catchment area. There were throughout the process issues with particles getting stuck by buildings in the model, even though it worked out in the end. This raised some concerns if the particle tracking approach is the right one to use when modelling urban catchment areas, thus, the conclusion that the concept is likely to be more successful when modelling catchment areas with greater focus on the watercourses.

8 References

Berghuijs, W.R., Aalbers, E.E., Larsen, J.R., Trancoso, R. & Woods, R.A. (2017). Recent changes in extreme floods across multiple continents. *Environmental Research Letters*, 12 (11), 114035. https://doi.org/10.1088/1748-9326/aa8847

Betson, R.P. & Marius, J.B. (1969). Source Areas of Storm Runoff. *Water Resources Research*, 5 (3), 574–582. https://doi.org/10.1029/WR005i003p00574

Beven, K. & Wood, E.F. (1983). Catchment geomorphology and the dynamics of runoff contributing areas. *Journal of Hydrology*, 65 (1), 139–158. https://doi.org/10.1016/0022-1694(83)90214-7

Beven, K.J. & Kirkby, M.J. (1979). A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. *Hydrological Sciences Bulletin*, 24 (1), 43–69. https://doi.org/10.1080/02626667909491834

Buchanan, B., Easton, Z.M., Schneider, R. & Walter, M.T. (2012). Incorporating Variable Source Area Hydrology into a Spatially Distributed Direct Runoff Model1. *JAWRA Journal of the American Water Resources Association*, 48 (1), 43–60. https://doi.org/10.1111/j.1752-1688.2011.00594.x

Dahlström, B. (2010). Regnintensitet – en molnfysikalisk betraktelse. 46

DHI ([u.å.]). *MIKE 21 - Hints and recommendations in applications with significant flooding and drying*. https://www.mikepoweredbydhi.com/upload/dhisoftwarearchive/papersanddocs/hydrodynamics/MIKE21SignificantFlodryGuidelines.pdf [2022-02-28]

DHI (2017a). *MIKE 21 & MIKE 3 Flow Model FM Hydrodynamic and Transport Module; Scientific Documentation*. Denmark: DHI Headquarters: DHI. https://manuals.mikepoweredbydhi.help/2017/Coast_and_Sea/MIKE_321_FM_Scientific_Doc.pdf [2022-02-28]

DHI (2017b). *MIKE 21 Flow Model FM Hydrodynamic Module; User Guide*. Denmark: DHI Headquarters. https://manuals.mikepoweredbydhi.help/2017/Coast_and_Sea/MIKE_FM_HD_2D.pdf [2022-02-28]

DHI (2017c). *MIKE 21 Flow Model FM Particle Tracking Module; User guide*. Denmark: DHI Headquarters. https://manuals.mikepoweredbydhi.help/2017/Coast_and_Sea/MIKE_FM_PT_2D.pdf [2022-02-28]

Dunne, T. (1983). Relation of field studies and modeling in the prediction of storm runoff. *Journal of Hydrology*, 65 (1), 25–48. https://doi.org/10.1016/0022-1694(83)90209-3

Elfström, D. & Stefansson, M. (2021). *How design storms with normally distributed intensities customized from precipitation radar data in Sweden affect the modeled hydraulic response to extreme rainfalls*. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1537251&dswid=-1306 [2022-02-23]

Falconer, R. h., Cobby, D., Smyth, P., Astle, G., Dent, J. & Golding, B. (2009). Pluvial flooding: new approaches in flood warning, mapping and risk management. *Journal of Flood Risk Management*, 2 (3), 198–208. https://doi.org/10.1111/j.1753-318X.2009.01034.x

Fiorentino, M., Manfreda, S. & Iacobellis, V. (2007). Peak runoff contributing area as hydrological signature of the probability distribution of floods. *Advances in Water Resources*, 30 (10), 2123–2134. https://doi.org/10.1016/j.advwatres.2006.11.017

Goel, M.K. (2011). Runoff Coefficient. I: Singh, V.P., Singh, P., & Haritashya, U.K. (red.) *Encyclopedia of Snow, Ice and Glaciers*. Dordrecht: Springer Netherlands, 952–953. https://doi.org/10.1007/978-90-481-2642-2_456

Grip, H., Rodhe, A. & Lehman, I. (1994). *Vattnets väg från regn till bäck*. 3., rev. uppl. Uppsala: Hallgren & Fallgren. https://go.exlibris.link/QBDyHchg
Gustafsson, L.-G. & Mårtensson, E. (2014). Kartläggning av skyfalls påverkan på samhällsviktig verksamhet : framtagande av metodik för utredning på kommunal nivå. 64
Hammarstrand, U. (2021). Moln. *Nationalencyklopedin*.. https://www-ne-se.ezproxy.its.uu.se/uppslagsverk/encyklopedi/l%C3%A5ng/moln [2021-10-12]
Hendriks, M. (2010). *Introduction to Physical Hydrology*. OUP Oxford.
Hernebring, C. (2006). *10års-regnets återkomst - förr och nu. Regndata för dimensionering/kontroll-beräkning av VA-system i tätorter*. (VA-Forsk rapport, 2006–04). Svenskt Vatten.
Hernebring, C. & Mårtensson, E. (2013). *Pluviala översvämningar - konsekvenser vid skyfall över tätorter, en kunskapsöversikt.* ((MSB567-13). Göteborg och Lund: Myndigheten för samhällskydd och beredskap.
Keifer, C.J. & Chu, H.H. (1957). Synthetic Storm Pattern for Drainage Design. *Journal of the Hydraulics Division*, 83 (4), 1332-1332–25. https://doi.org/10.1061/JYCEAJ.0000104
Marsalek, J. (1980). Runoff control on urbanizing catchments.
Pan, C., Wang, X., Liu, L., Huang, H. & Wang, D. (2017). Improvement to the Huff Curve for Design Storms and Urban Flooding Simulations in Guangzhou, China. *Water*, 9 (6), 411. https://doi.org/10.3390/w9060411
Qin, H., Li, Z. & Fu, G. (2013). The effects of low impact development on urban flooding under different rainfall characteristics. *Journal of Environmental Management*, 129, 577–585. https://doi.org/10.1016/j.jenvman.2013.08.026
Rivard, G. (1996). Design Storm Events for Urban Drainage Based on Historical Rainfall Data: a Conceptual Framework for a Logical Approach. *Journal of Water Management Modeling*,. https://doi.org/10.14796/JWMM.R191-12
Rogers, W.F. (1972). New concept in hydrograph analysis. *Water Resources Research*, 8 (4), 973–981. https://doi.org/10.1029/WR008i004p00973
Svenskt vatten (2011). *Nederbördsdata vid dimensionering och analys av avloppssystem*. 1. utgåvan. Stockholm: Svenskt vatten. https://go.exlibris.link/S3PzdFXs [2021-09-09]
Tanaka, T., Kiyohara, K. & Tachikawa, Y. (2020). Comparison of fluvial and pluvial flood risk curves in urban cities derived from a large ensemble climate simulation dataset: A case study in Nagoya, Japan. *Journal of Hydrology*, 584, 124706. https://doi.org/10.1016/j.jhydrol.2020.124706
Venutelli, M. (2005). A Constitutive Explanation of Manning's Formula. *Meccanica*, 40 (3), 281–289. https://doi.org/10.1007/s11012-005-6529-5
Watt, E. & Marsalek, J. (2013). Critical review of the evolution of the design storm event concept. *Canadian Journal of Civil Engineering*, 40 (2), 105–113. https://doi.org/10.1139/cjce-2011-0594
Yang, Y., Sun, L., Li, R., Yin, J. & Yu, D. (2020). Linking a Storm Water Management Model to a Novel Two-Dimensional Model for Urban Pluvial Flood Modeling. *International Journal of Disaster Risk Science*, 11 (4), 508–518. https://doi.org/10.1007/s13753-020-00278-7

Appendices

Appendix A

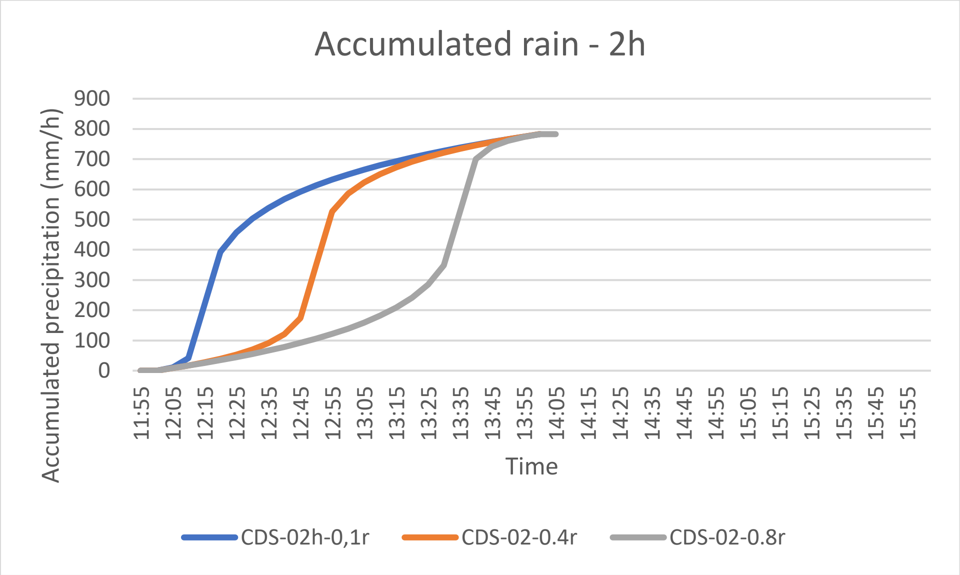

Figure A1: Accumulated rainfall of the 2h design storm with varied r-value

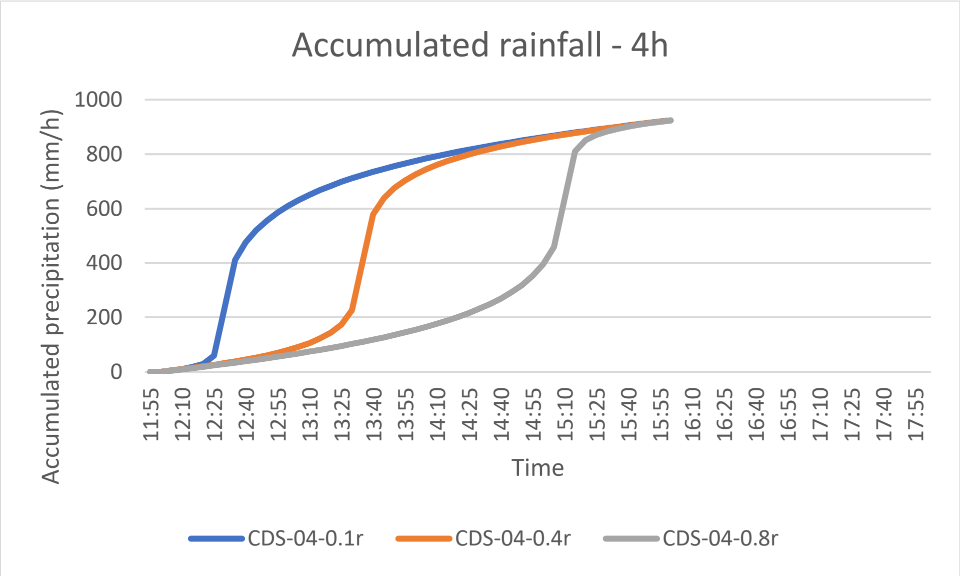

Figure A2: Accumulated rainfall of the 4h design storm with varied r-value

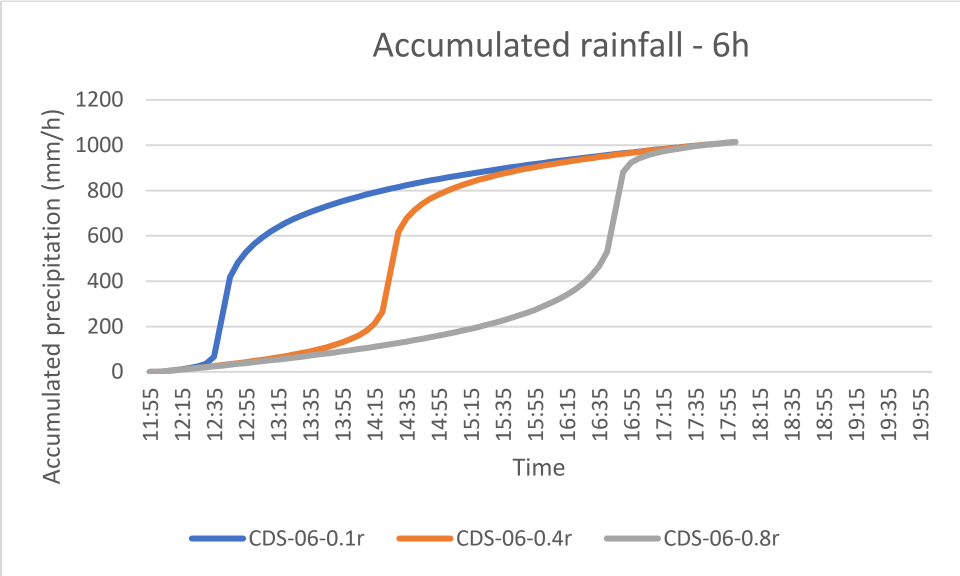

Figure A3: Accumulated rainfall of the 6h design storm with varied r-value